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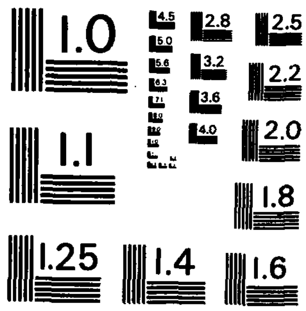

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PLASMA FORMULARY

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Revised 1983

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NRL PLASMA FORMULARY

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CONTENTS

NUMERICAL AND ALGEBRAIC

Gain in decibels of P_2 relative to P_1

$$G = 10 \log_{10} (P_2/P_1).$$

To within two percent

$$(2\pi)^{1/2} \simeq 2.5; \quad \pi^2 \simeq 10; \quad e^3 \simeq 20; \quad 2^{10} \simeq 10^3.$$

Euler-Mascheroni constant[1] $\gamma = 0.57722$

Gamma Function $\Gamma(x+1) = x\Gamma(x)$

$$\begin{aligned}
\Gamma(1/6) &= 5.5663 \\
\Gamma(1/5) &= 4.5908 \\
\Gamma(1/4) &= 3.6256 \\
\Gamma(1/3) &= 2.6789 \\
\Gamma(2/5) &= 2.2182 \\
\Gamma(1/2) &= 1.7725 = \pi^{1/2} \\
\Gamma(3/5) &= 1.4892 \\
\Gamma(2/3) &= 1.3541 \\
\Gamma(3/4) &= 1.2254 \\
\Gamma(4/5) &= 1.1642 \\
\Gamma(5/6) &= 1.1288 \\
\Gamma(1) &= 1.0
\end{aligned}$$

Binomial Theorem (good for $|x| < 1$ or α = positive integer):

$$(1+x)^\alpha = \sum_{k=0}^{\infty} \binom{\alpha}{k} x^k = 1 + \alpha x + \frac{\alpha(\alpha-1)}{2\,!} x^2 + \frac{\alpha(\alpha-1)(\alpha-2)}{3\,!} x^3 + \ldots$$

Rothe-Hagen identity[2] (good for all complex x, y, z except when singular):

$$\sum_{k=0}^{n} \frac{x}{x+kz} \binom{x+kz}{k} \frac{y}{y+(n-k)z} \binom{y+(n-k)z}{n-k} = \frac{x+y}{x+y+nz} \binom{x+y+nz}{n}$$

VECTOR IDENTITIES[3]

Notation: f, g, etc., are scalars; **A**, **B**, etc. are vectors; **T** is a tensor

(1) $\mathbf{A} \cdot \mathbf{B} \times \mathbf{C} = \mathbf{A} \times \mathbf{B} \cdot \mathbf{C} = \mathbf{B} \cdot \mathbf{C} \times \mathbf{A} = \mathbf{B} \times \mathbf{C} \cdot \mathbf{A} = \mathbf{C} \cdot \mathbf{A} \times \mathbf{B} = \mathbf{C} \times \mathbf{A} \cdot \mathbf{B}$

(2) $\mathbf{A} \times (\mathbf{B} \times \mathbf{C}) = (\mathbf{C} \times \mathbf{B}) \times \mathbf{A} = (\mathbf{A} \cdot \mathbf{C})\, \mathbf{B} - (\mathbf{A} \cdot \mathbf{B})\, \mathbf{C}$

(3) $\mathbf{A} \times (\mathbf{B} \times \mathbf{C}) + \mathbf{B} \times (\mathbf{C} \times \mathbf{A}) + \mathbf{C} \times (\mathbf{A} \times \mathbf{B}) = 0$

(4) $(\mathbf{A} \times \mathbf{B}) \cdot (\mathbf{C} \times \mathbf{D}) = (\mathbf{A} \cdot \mathbf{C})\,(\mathbf{B} \cdot \mathbf{D}) - (\mathbf{A} \cdot \mathbf{D})\,(\mathbf{B} \cdot \mathbf{C})$

(5) $(\mathbf{A} \times \mathbf{B}) \times (\mathbf{C} \times \mathbf{D}) = (\mathbf{A} \times \mathbf{B} \cdot \mathbf{D})\, \mathbf{C} - (\mathbf{A} \times \mathbf{B} \cdot \mathbf{C})\, \mathbf{D}$

(6) $\nabla(fg) = \nabla\,(gf) = f\nabla g + g\nabla f$

(7) $\nabla \cdot (f\mathbf{A}) = f\nabla \cdot \mathbf{A} + \mathbf{A} \cdot \nabla f$

(8) $\nabla \times (f\mathbf{A}) = f\nabla \times \mathbf{A} + \nabla f \times \mathbf{A}$

(9) $\nabla \cdot (\mathbf{A} \times \mathbf{B}) = \mathbf{B} \cdot \nabla \times \mathbf{A} - \mathbf{A} \cdot \nabla \times \mathbf{B}$

(10) $\nabla \times (\mathbf{A} \times \mathbf{B}) = \mathbf{A}\,(\nabla \cdot \mathbf{B}) - \mathbf{B}\,(\nabla \cdot \mathbf{A}) + (\mathbf{B} \cdot \nabla)\,\mathbf{A} - (\mathbf{A} \cdot \nabla)\,\mathbf{B}$

(11) $\mathbf{A} \times (\nabla \times \mathbf{B}) = (\nabla \mathbf{B}) \cdot \mathbf{A} - (\mathbf{A} \cdot \nabla)\mathbf{B}$

(12) $\nabla\,(\mathbf{A} \cdot \mathbf{B}) = \mathbf{A} \times (\nabla \times \mathbf{B}) + \mathbf{B} \times (\nabla \times \mathbf{A}) + (\mathbf{A} \cdot \nabla)\,\mathbf{B} + (\mathbf{B} \cdot \nabla)\,\mathbf{A}$

(13) $\nabla^2 f = \nabla \cdot \nabla f$

(14) $\nabla^2 \mathbf{A} = \nabla\,(\nabla \cdot \mathbf{A}) - \nabla \times \nabla \times \mathbf{A}$

(15) $\nabla \times \nabla f = 0$

(16) $\nabla \cdot \nabla \times \mathbf{A} = 0$

If $\mathbf{e}_1$, $\mathbf{e}_2$, $\mathbf{e}_3$ are orthonormal unit vectors, a second-order tensor **T** can be written in the dyadic form

(17) $\mathbf{T} = \sum_{i,j} T_{ij}\mathbf{e}_i\mathbf{e}_j$

In cartesian coordinates the divergence of a tensor is a vector with components

(18) $(\nabla \cdot \mathbf{T})_i = \sum_j (\partial T_{ji}/\partial x_j)$

[This definition is required for consistency with Eq. (28)]. In general

(19) $\nabla \cdot (\mathbf{AB}) = (\nabla \cdot \mathbf{A})\,\mathbf{B} + (\mathbf{A} \cdot \nabla)\,\mathbf{B}$

(20) $\nabla \cdot (f\mathbf{T}) = \nabla f \cdot \mathbf{T} + f\nabla \cdot \mathbf{T}$

Let $\mathbf{r} = \mathbf{i}x + \mathbf{j}y + \mathbf{k}z$ be the radius vector of magnitude r, from the origin to the point x,y,z. Then

(21) $\nabla \cdot \mathbf{r} = 3$

(22) $\nabla \times \mathbf{r} = 0$

(23) $\nabla r = \mathbf{r}/r$

(24) $\nabla(1/r) = -\mathbf{r}/r^3$

(25) $\nabla \cdot (\mathbf{r}/r^3) = 4\pi\delta(\mathbf{r})$

If V is a volume enclosed by a surface S and $d\mathbf{S} = \mathbf{n}dS$ where $\mathbf{n}$ is the unit normal outward from V,

(26) $\int_V dV \nabla f = \int_S d\mathbf{S} f$

(27) $\int_V dV \nabla \cdot \mathbf{A} = \int_S d\mathbf{S} \cdot \mathbf{A}$

(28) $\int_V dV \nabla \cdot \mathbf{T} = \int_S d\mathbf{S} \cdot \mathbf{T}$

(29) $\int_V dV \nabla \times \mathbf{A} = \int_S d\mathbf{S} \times \mathbf{A}$

(30) $\int_V dV (f\nabla^2 g - g\nabla^2 f) = \int_S d\mathbf{S} \cdot (f\nabla g - g\nabla f)$

(31) $\int_V dV (\mathbf{A} \cdot \nabla \times \nabla \times \mathbf{B} - \mathbf{B} \cdot \nabla \times \nabla \times \mathbf{A}) = \int_S d\mathbf{S} \cdot (\mathbf{B} \times \nabla \times \mathbf{A} - \mathbf{A} \times \nabla \times \mathbf{B})$.

If S is an open surface bounded by the contour C of which the line element is $d\mathbf{l}$,

(32) $\int_S d\mathbf{S} \times \nabla f = \oint_C d\mathbf{l} f$

(33) $\int_S d\mathbf{S} \cdot \nabla \times \mathbf{A} = \oint_C d\mathbf{l} \cdot \mathbf{A}$

(34) $\int_S (d\mathbf{S} \times \nabla) \times \mathbf{A} = \oint_C d\mathbf{l} \times \mathbf{A}$

(35) $\int_S d\mathbf{S} \cdot (\nabla f \times \nabla g) = \oint_C f dg = -\oint_C g df$

DIFFERENTIAL OPERATORS IN CURVILINEAR COORDINATES[4]

Cylindrical Coordinates

Divergence

$$\nabla \cdot \mathbf{A} = \frac{1}{r}\frac{\partial}{\partial r}(rA_r) + \frac{1}{r}\frac{\partial A_\phi}{\partial \phi} + \frac{\partial A_z}{\partial z}$$

Gradient

$$(\nabla f)_r = \frac{\partial f}{\partial r}; \quad (\nabla f)_\phi = \frac{1}{r}\frac{\partial f}{\partial \phi}; \quad (\nabla f)_z = \frac{\partial f}{\partial z};$$

Curl

$$(\nabla \times \mathbf{A})_r = \frac{1}{r}\frac{\partial A_z}{\partial \phi} - \frac{\partial A_\phi}{\partial z}$$

$$(\nabla \times \mathbf{A})_\phi = \frac{\partial A_r}{\partial z} - \frac{\partial A_z}{\partial r}$$

$$(\nabla \times \mathbf{A})_z = \frac{1}{r}\frac{\partial}{\partial r}(rA_\phi) - \frac{1}{r}\frac{\partial A_r}{\partial \phi}$$

Laplacian

$$\nabla^2 f = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial f}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 f}{\partial \phi^2} + \frac{\partial^2 f}{\partial z^2}$$

Laplacian of a vector

$$(\nabla^2 \mathbf{A})_r = \nabla^2 A_r - \frac{2}{r^2}\frac{\partial A_\phi}{\partial \phi} - \frac{A_r}{r^2}$$

$$(\nabla^2 \mathbf{A})_\phi = \nabla^2 A_\phi + \frac{2}{r^2}\frac{\partial A_r}{\partial \phi} - \frac{A_\phi}{r^2}$$

$$(\nabla^2 \mathbf{A})_z = \nabla^2 A_z$$

Components of $(\mathbf{A}\cdot\nabla)\mathbf{B}$

$$(\mathbf{A}\cdot\nabla\mathbf{B})_r = A_r\frac{\partial B_r}{\partial r} + \frac{A_\phi}{r}\frac{\partial B_r}{\partial \phi} + A_z\frac{\partial B_r}{\partial z} - \frac{A_\phi B_\phi}{r}$$

$$(\mathbf{A}\cdot\nabla\mathbf{B})_\phi = A_r\frac{\partial B_\phi}{\partial r} + \frac{A_\phi}{r}\frac{\partial B_\phi}{\partial \phi} + A_z\frac{\partial B_\phi}{\partial z} + \frac{A_\phi B_r}{r}$$

$$(\mathbf{A}\cdot\nabla\mathbf{B})_z = A_r\frac{\partial B_z}{\partial r} + \frac{A_\phi}{r}\frac{\partial B_z}{\partial \phi} + A_z\frac{\partial B_z}{\partial z}$$

Divergence of a tensor

$$(\nabla\cdot\mathbf{T})_r = \frac{1}{r}\frac{\partial}{\partial r}(rT_{rr}) + \frac{1}{r}\frac{\partial}{\partial \phi}(T_{\phi r}) + \frac{\partial T_{zr}}{\partial z} - \frac{1}{r}T_{\phi\phi}$$

$$(\nabla\cdot\mathbf{T})_\phi = \frac{1}{r}\frac{\partial}{\partial r}(rT_{r\phi}) + \frac{1}{r}\frac{\partial T_{\phi\phi}}{\partial \phi} + \frac{\partial T_{z\phi}}{\partial z} + \frac{1}{r}T_{\phi r}$$

$$(\nabla\cdot\mathbf{T})_z = \frac{1}{r}\frac{\partial}{\partial r}(rT_{rz}) + \frac{1}{r}\frac{\partial T_{\phi z}}{\partial \phi} + \frac{\partial T_{zz}}{\partial z}$$

Spherical Coordinates

Divergence

$$\nabla \cdot \mathbf{A} = \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 A_r) + \frac{1}{r \sin\theta}\frac{\partial}{\partial\theta}(A_\theta \sin\theta) + \frac{1}{r\sin\theta}\frac{\partial A_\phi}{\partial\phi}$$

Gradient

$$(\nabla f)_r = \frac{\partial f}{\partial r}; \quad (\nabla f)_\theta = \frac{1}{r}\frac{\partial f}{\partial\theta}; \quad (\nabla f)_\phi = \frac{1}{r\sin\theta}\frac{\partial f}{\partial\phi};$$

Curl

$$(\nabla \times \mathbf{A})_r = \frac{1}{r\sin\theta}\frac{\partial}{\partial\theta}(A_\phi \sin\theta) - \frac{1}{r\sin\theta}\frac{\partial A_\theta}{\partial\phi}$$

$$(\nabla \times \mathbf{A})_\theta = \frac{1}{r\sin\theta}\frac{\partial A_r}{\partial\phi} - \frac{1}{r}\frac{\partial}{\partial r}(rA_\phi)$$

$$(\nabla \times \mathbf{A})_\phi = \frac{1}{r}\frac{\partial}{\partial r}(rA_\theta) - \frac{1}{r}\frac{\partial A_r}{\partial\theta}$$

Laplacian

$$\nabla^2 f = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial f}{\partial r}\right) + \frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial f}{\partial\theta}\right) + \frac{1}{r^2\sin^2\theta}\frac{\partial^2 f}{\partial\phi^2}$$

Laplacian of a vector

$$(\nabla^2\mathbf{A})_r = \nabla^2 A_r - \frac{2A_r}{r^2} - \frac{2}{r^2}\frac{\partial A_\theta}{\partial\theta} - \frac{2A_\theta\cot\theta}{r^2} - \frac{2}{r^2\sin\theta}\frac{\partial A_\phi}{\partial\phi}$$

$$(\nabla^2\mathbf{A})_\theta = \nabla^2 A_\theta + \frac{2}{r^2}\frac{\partial A_r}{\partial\theta} - \frac{A_\theta}{r^2\sin^2\theta} - \frac{2\cos\theta}{r^2\sin^2\theta}\frac{\partial A_\phi}{\partial\phi}$$

$$(\nabla^2\mathbf{A})_\phi = \nabla^2 A_\phi - \frac{A_\phi}{r^2\sin^2\theta} + \frac{2}{r^2\sin\theta}\frac{\partial A_r}{\partial\phi} + \frac{2\cos\theta}{r^2\sin^2\theta}\frac{\partial A_\theta}{\partial\phi}$$

Components of $(\mathbf{A} \cdot \nabla)\mathbf{B}$

$$(\mathbf{A} \cdot \nabla \mathbf{B})_r = A_r \frac{\partial B_r}{\partial r} + \frac{A_\theta}{r} \frac{\partial B_r}{\partial \theta} + \frac{A_\phi}{r \sin \theta} \frac{\partial B_r}{\partial \phi} - \frac{A_\theta B_\theta + A_\phi B_\phi}{r}$$

$$(\mathbf{A} \cdot \nabla \mathbf{B})_\theta = A_r \frac{\partial B_\theta}{\partial r} + \frac{A_\theta}{r} \frac{\partial B_\theta}{\partial \theta} + \frac{A_\phi}{r \sin \theta} \frac{\partial B_\theta}{\partial \phi} + \frac{A_\theta B_r}{r} - \frac{A_\phi B_\phi \cot \theta}{r}$$

$$(\mathbf{A} \cdot \nabla \mathbf{B})_\phi = A_r \frac{\partial B_\phi}{\partial r} + \frac{A_\theta}{r} \frac{\partial B_\phi}{\partial \theta} + \frac{A_\phi}{r \sin \theta} \frac{\partial B_\phi}{\partial \phi} + \frac{A_\phi B_r}{r} + \frac{A_\phi B_\theta \cot \theta}{r}$$

Divergence of a tensor

$$(\nabla \cdot \mathbf{T})_r = \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 T_{rr}) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta} (T_{\theta r} \sin \theta) + \frac{1}{r \sin \theta} \frac{\partial T_{\phi r}}{\partial \phi} - \frac{T_{\theta\theta} + T_{\phi\phi}}{r}$$

$$(\nabla \cdot \mathbf{T})_\theta = \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 T_{r\theta}) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta} (T_{\theta\theta} \sin \theta) + \frac{1}{r \sin \theta} \frac{\partial T_{\phi\theta}}{\partial \phi} + \frac{T_{\theta r}}{r} - \frac{\cot \theta}{r} T_{\phi\phi}$$

$$(\nabla \cdot \mathbf{T})_\phi = \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 T_{r\phi}) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta} (T_{\theta\phi} \sin \theta) + \frac{1}{r \sin \theta} \frac{\partial T_{\phi\phi}}{\partial \phi} + \frac{T_{\phi r}}{r} + \frac{\cot \theta}{r} T_{\phi\theta}$$

DIMENSIONS AND UNITS

To get the value of a quantity in Gaussian units, multiply the value expressed in mks units by the conversion factor. Multiples of 3 in the conversion factors result from approximating the speed of light $c = 2.9979 \times 10^{10}$ cm/sec $\approx 3 \times 10^{10}$ cm/sec.

Phvsical Quantity	Sym-bol	Dimensions		Rationalized mks	Conversion Factor	Gaussian
		mks Units	Gaussian Units			
Capacitance	C	$\frac{t^2q^2}{ml^2}$	l	farad	9×10^{11}	cm
Charge	q	q	$\frac{m^{1/2}l^{3/2}}{t}$	coulomb	3×10^{9}	statcoulomb
Charge density	ρ	$\frac{q}{l^3}$	$\frac{m^{1/2}}{l^{3/2}t}$	coulomb/m^3	3×10^{3}	statcoulomb/ cm^3
Conductance		$\frac{tq^2}{ml^2}$	$\frac{l}{t}$	siemens	9×10^{11}	cm/sec
Conductivity	σ	$\frac{tq^2}{ml^3}$	$\frac{1}{t}$	siemens/m	9×10^{9}	sec^{-1}
Current	I	$\frac{q}{t}$	$\frac{m^{1/2}l^{3/2}}{t^2}$	ampere	3×10^{9}	statampere
Current density	$\mathbf{J}$	$\frac{q}{l^2t}$	$\frac{m^{1/2}}{l^{1/2}t^2}$	ampere/m^2	3×10^{5}	statampere/ cm^2
Density	ρ	$\frac{m}{l^3}$	$\frac{m}{l^3}$	kg/m^3	10^{-3}	g/cm^3
Displacement	$\mathbf{D}$	$\frac{q}{l^2}$	$\frac{m^{1/2}}{l^{1/2}t}$	coulomb/m^2	$12\pi \times 10^{5}$	statcoulomb/ cm^2
Electric field	$\mathbf{E}$	$\frac{ml}{t^2q}$	$\frac{m^{1/2}}{l^{1/2}t}$	volt/m	$\frac{1}{3} \times 10^{-4}$	statvolt/cm
Electromotance	$\mathcal{E}$, Emf	$\frac{ml^2}{t^2q}$	$\frac{m^{1/2}l^{1/2}}{t}$	volt	$\frac{1}{3} \times 10^{-2}$	statvolt
Energy	U, W	$\frac{ml^2}{t^2}$	$\frac{ml^2}{t^2}$	joule	10^{7}	erg
Energy density	w, ϵ	$\frac{m}{lt^2}$	$\frac{m}{lt^2}$	joule/m^3	10	erg/cm^3

Physical Quantity	Symbol	Dimensions		Rationalized mks	Conversion Factor	Gaussian
		mks Units	Gaussian Units			
Force	**F**	$\frac{m\ell}{t^2}$	$\frac{m\ell}{t^2}$	newton	10^5	dyne
Frequency	f, ν	$\frac{1}{t}$	$\frac{1}{t}$	hertz	1	hertz
Impedance	Z	$\frac{m\ell^2}{tq^2}$	$\frac{t}{\ell}$	ohm	$\frac{1}{9} \times 10^{-11}$	sec/cm
Inductance	L	$\frac{m\ell^2}{q^2}$	$\frac{t^2}{\ell}$	henry	$\frac{1}{9} \times 10^{-11}$	sec^2/cm
Length	ℓ	ℓ	ℓ	meter (m)	10^2	centimeter (cm)
Magnetic intensity	**H**	$\frac{q}{\ell t}$	$\frac{m^{1/2}}{\ell^{1/2}t}$	ampere-turn/m	$4\pi \times 10^{-3}$	oersted
Magnetic flux	Φ	$\frac{m\ell^2}{tq}$	$\frac{m^{1/2}\ell^{3/2}}{t}$	weber	10^8	maxwell
Magnetic induction	**B**	$\frac{m}{tq}$	$\frac{m^{1/2}}{\ell^{1/2}t}$	tesla	10^4	gauss
Magnetic moment	m	$\frac{l^2 q}{t}$	$\frac{m^{1/2}l^{5/2}}{t}$	ampere-m^2	10^3	oersted-cm^3
Magnetization	**M**	$\frac{q}{\ell t}$	$\frac{m^{1/2}}{\ell^{1/2}t}$	ampere-turn/m	10^{-3}	oersted
Magnetomotance	$\mathcal{M}$, Mmf	$\frac{q}{t}$	$\frac{m^{1/2}\ell^{1/2}}{t^2}$	ampere-turn	$\frac{4\pi}{10}$	gilbert
Mass	m, M	m	m	kilogram (kg)	10^3	gram (g)
Momentum	**p**, **P**	$\frac{m\ell}{t}$	$\frac{m\ell}{t}$	kg-m/sec	10^5	g-cm/sec
Momentum density		$\frac{m}{\ell^2 t}$	$\frac{m}{\ell^2 t}$	kg/m^2-sec	10^{-1}	g/cm^2-sec
Permeability	μ	$\frac{m\ell}{q^2}$	1	henry/m	$\frac{1}{4\pi} \times 10^7$	—

Physical Quantity	Symbol	Dimensions: mks Units	Dimensions: Gaussian Units	Rationalized mks	Conversion Factor	Gaussian
Permittivity	ϵ	$\frac{t^2 q^2}{m \ell^3}$	1	farad/m	$36\pi \times 10^9$	—
Polarization	**P**	$\frac{q}{\ell^2}$	$\frac{m^{1/2}}{\ell^{1/2} t}$	coulomb/m^2	3×10^5	statcoulomb/cm^2
Potential	V, ϕ	$\frac{m \ell^2}{t^2 q}$	$\frac{m^{1/2} \ell^{1/2}}{t}$	volt	$\frac{1}{3} \times 10^{-2}$	statvolt
Power	P	$\frac{m \ell^2}{t^3}$	$\frac{m \ell^2}{t^3}$	watt	10^7	erg/sec
Power density		$\frac{m}{\ell t^3}$	$\frac{m}{\ell t^3}$	watt/m^3	10	erg/cm^3-sec
Pressure	p	$\frac{m}{\ell t^2}$	$\frac{m}{\ell t^2}$	pascal	10	dyne/cm^2
Reluctance	$\mathcal{R}$	$\frac{q^2}{m \ell^2}$	$\frac{1}{\ell}$	ampere-turn/weber	$4\pi \times 10^{-9}$	cm^{-1}
Resistance	R	$\frac{m \ell^2}{t q^2}$	$\frac{t}{\ell}$	ohm	$\frac{1}{9} \times 10^{-11}$	sec/cm
Resistivity	η, ρ	$\frac{m \ell^3}{t q^2}$	t	ohm-m	$\frac{1}{9} \times 10^{-9}$	sec
Thermal conductivity	κ	$\frac{m \ell}{t^3}$	$\frac{m \ell}{t^3}$	watt/m-deg (K)	10^5	erg/cm-sec-deg (K)
Time	t	t	t	second (sec)	1	second
Vector potential	**A**	$\frac{m \ell}{t q}$	$\frac{m^{1/2} \ell^{1/2}}{t}$	weber/m	10^6	gauss-cm
Velocity	**v**	$\frac{\ell}{t}$	$\frac{\ell}{t}$	m/sec	10^2	cm/sec
Viscosity	η, μ	$\frac{m}{\ell t}$	$\frac{m}{\ell t}$	kg/m-sec	10	poise
Vorticity	ζ	$\frac{1}{t}$	$\frac{1}{t}$	sec^{-1}	1	sec^{-1}
Work	W	$\frac{m \ell^2}{t^2}$	$\frac{m \ell^2}{t^2}$	joule	10^7	erg

INTERNATIONAL SYSTEM (SI) NOMENCLATURE[5]

Physical Quantity	Name of Unit	Symbol for Unit	Physical Quantity	Name of Unit	Symbol for Unit
*length	meter	m	electric potential	volt	V
*mass	kilogram	kg	electric resistance	ohm	Ω
*time	second	s	electric conductance	siemens	S
*electric current	ampere	A	electric capacitance	farad	F
*thermodynamic temperature	kelvin	K	magnetic flux	weber	Wb
*amount of substance	mole	mol	inductance	henry	H
*luminous intensity	candela	cd	magnetic flux density	tesla	T
†plane angle	radian	rad	luminous flux	lumen	lm
†solid angle	steradian	sr	illuminance	lux	lx
frequency	hertz	Hz	activity (of a radioactive source)	becquerel	Bq
energy	joule	J	absorbed dose (of ionizing radiation)	gray	Gy
force	newton	N			
pressure	pascal	Pa			
power	watt	W			
electric charge	coulomb	C			

*SI Base Unit
†Supplementary Unit

METRIC PREFIXES

Multiple	Prefix	Symbol	Multiple	Prefix	Symbol
10^{-1}	deci	d	10	deca	da
10^{-2}	centi	c	10^{2}	hecto	h
10^{-3}	milli	m	10^{3}	kilo	k
10^{-6}	micro	μ	10^{6}	mega	M
10^{-9}	nano	n	10^{9}	giga	G
10^{-12}	pico	p	10^{12}	tera	T
10^{-15}	femto	f	10^{15}	peta	P
10^{-18}	atto	a	10^{18}	exa	E

PHYSICAL CONSTANTS (SI)[6]

Physical Quantity	Symbol	Value	Units
Boltzmann constant	k	1.3807×10^{-23}	$J\ K^{-1}$
Elementary charge	e	1.6022×10^{-19}	C
Electron mass	m_e	9.1095×10^{-31}	kg
Proton mass	m_p	1.6726×10^{-27}	kg
Gravitational constant	G	6.6720×10^{-11}	$m^3\ s^{-2}\ kg^{-1}$
Planck constant	h $\hbar = h/2\pi$	6.6262×10^{-34} 1.0546×10^{-34}	J s J s
Speed of light in vacuum	c	2.9979×10^{8}	$m\ s^{-1}$
Permittivity of free space	ϵ_0	8.8542×10^{-12}	$F\ m^{-1}$
Permeability of free space	μ_0	$4\pi \times 10^{-7}$	$H\ m^{-1}$
Proton/electron mass ratio	m_p/m_e	1.8362×10^{3}	
Electron charge/mass ratio	e/m_e	1.7588×10^{11}	$C\ kg^{-1}$
Rydberg constant	$R_\infty = \dfrac{2\pi^2 me^4}{ch^3}$	1.0974×10^{7}	m^{-1}
Bohr radius	$a_0 = \hbar/me^2$	5.2918×10^{-11}	m
Atomic cross section	πa_0^2	8.7974×10^{-21}	m^2
Classical electron radius	$r_e = e^2/mc^2$	2.8179×10^{-15}	m
Thomson cross section	$(8\pi/3)r_e^2$	6.6524×10^{-29}	m^2
Compton wavelength of electron	h/m_ec $\hbar/m_ec$	2.4263×10^{-12} 3.8616×10^{-13}	m m
Fine-structure constant	$\alpha = e^2/\hbar c$ α^{-1}	7.2974×10^{-3} 137.04	
First radiation constant	$c_1 = 2\pi hc^2$	3.7418×10^{-2}	$W\ m^2$
Second radiation constant	$c_2 = hc/k$	1.4388×10^{-2}	m K
Stefan-Boltzmann constant	σ	5.6703×10^{-8}	$W\ m^{-2}\ K^{-4}$

Physical Quantity	Symbol	Value	Units
Wavelength associated with 1 eV	λ_0	1.2399×10^{-6}	m
Frequency associated with 1 eV	ν_0	2.4180×10^{14}	Hz
Wave number associated with 1 eV	k_0	8.0655×10^{5}	m^{-1}
Energy associated with 1 eV		1.6022×10^{-19}	J
Energy associated with 1 m^{-1}		1.9865×10^{-25}	J
Energy associated with 1 Rydberg		13.606	eV
Energy associated with 1 Kelvin		8.6173×10^{-5}	eV
Temperature associated with 1 eV		1.1605×10^{4}	K
Avogadro number	N_A	6.0220×10^{23}	mol^{-1}
Faraday constant	$F = N_A e$	9.6485×10^{4}	C mol^{-1}
Gas constant	$R = N_A k$	8.3144	J K^{-1} mol^{-1}
Loschmidt's number (no. density at STP)	n_0	2.6868×10^{25}	m^{-3}
Atomic mass unit	m_u	1.6606×10^{-27}	kg
Standard temperature	T_0	273.16	K
Atmospheric pressure	$p_0 = n_0 k T_0$	1.0133×10^{5}	Pa
Pressure of 1 mm Hg (torr)		1.3332×10^{2}	Pa
Molar volume at STP	$V_0 = RT_0/p_0$	2.2415×10^{-2}	m^3
Molar weight of air	M_{air}	2.8971×10^{-2}	kg
calorie (cal)		4.1868	J
Gravitational acceleration	g	9.8067	m s^{-2}

PHYSICAL CONSTANTS (cgs)

Physical Quantity	Symbol	Value	Units
Boltzmann constant	k	1.3807×10^{-16}	erg/deg (K)
Elementary charge	e	4.8032×10^{-10}	statcoulomb
Electron mass	m_e	9.1095×10^{-28}	g
Proton mass	m_p	1.6726×10^{-24}	g
Gravitational constant	G	6.6720×10^{-8}	dyne-cm²/g²
Planck constant	h $\hbar = h/2\pi$	6.6262×10^{-27} 1.0546×10^{-27}	erg-sec erg-sec
Speed of light in vacuum	c	2.9979×10^{10}	cm/sec
Proton/electron mass ratio	m_p/m_e	1.8362×10^{3}	
Electron charge/mass ratio	e/m_e	5.2728×10^{17}	statcoulomb/g
Rydberg constant	$R_\infty = \dfrac{2\pi^2 me^4}{ch^3}$	1.0974×10^{5}	cm⁻¹
Bohr radius	$a_0 = \hbar^2/me^2$	5.2918×10^{-9}	cm
Atomic cross section	πa_0^2	8.7974×10^{-17}	cm²
Classical electron radius	$r_e = e^2/mc^2$	2.8179×10^{-13}	cm
Thomson cross section	$(8\pi/3)\,r_e^2$	6.6524×10^{-25}	cm²
Compton wavelength of electron	$h/m_e c$ $\hbar/m_e c$	2.4263×10^{-10} 3.8616×10^{-11}	cm cm
Fine-structure constant	$\alpha = e^2/\hbar c$ α^{-1}	7.2974×10^{-3} 137.04	
First radiation constant	$c_1 = 2\pi hc^2$	3.7418×10^{-5}	erg-cm²/sec
Second radiation constant	$c_2 = hc/k$	1.4388	cm-deg (K)
Stefan-Boltzmann constant	σ	5.6703×10^{-5}	erg/cm²-sec-deg⁴
Wavelength associated with 1 eV	λ_0	1.2399×10^{-4}	cm

Physical Quantity	Symbol	Value	Units
Frequency associated with 1 eV	ν_0	2.4180×10^{14}	Hz
Wave number associated with 1 eV	k_0	8.0655×10^{3}	cm^{-1}
Energy associated with 1 eV		1.6022×10^{-12}	erg
Energy associated with 1 cm^{-1}		1.9865×10^{-16}	erg
Energy associated with 1 Rydberg		13.606	eV
Energy associated with 1° Kelvin		8.6173×10^{-5}	eV
Temperature associated with 1 eV		1.1605×10^{4}	deg (K)
Avogadro number	N_A	6.0220×10^{23}	mol^{-1}
Faraday constant	$F = N_A e$	2.8925×10^{14}	statcoulomb/mol
Gas constant	$R = N_A k$	8.3144×10^{7}	erg/deg-mol
Loschmidt's number (no. density at STP)	n_0	2.6868×10^{19}	cm^{-3}
Atomic mass unit	m_u	1.6606×10^{-24}	g
Standard temperature	T_0	273.16	deg (K)
Atmospheric pressure	$p_0 = n_0 k T_0$	1.0133×10^{6}	dyne/cm^2
Pressure of 1 mmHg (torr)		1.3332×10^{3}	dyne/cm^2
Molar volume at STP	$V_0 = RT_0/p_0$	2.2415×10^{4}	cm^3
Molar weight of air	M_{air}	28.971	g
calorie (cal)		4.1868×10^{7}	erg
Gravitational acceleration	g	980.67	cm/sec^2

FORMULA CONVERSION[7]

Here $\alpha = 10^2$ cm m^{-1}, $\beta = 10^7$ erg J^{-1}, $\epsilon_0 = 8.8542 \times 10^{-12}$ F m^{-1}, $\mu_0 = 4\pi \times 10^{-7}$ H m^{-1}, $c = (\epsilon_0\mu_0)^{-1/2} = 2.9979 \times 10^8$ m s^{-1}, and $\hbar = 1.0546 \times 10^{-34}$ J s. To derive a dimensionally correct SI formula from one expressed in Gaussian units, substitute for each quantity according to $\bar{Q} = \bar{k}Q$, where $\bar{k}$ is the coefficient in the second column of the table corresponding to Q (tildes denote variables expressed in Gaussian units). Thus the formula $\bar{a}_0 = \bar{\hbar}^2/\bar{m}\bar{e}^2$ for the Bohr radius becomes $\alpha a_0 = (\hbar\beta)^2/[(m\beta/\alpha^2)\,(e^2\alpha\beta/4\pi\epsilon_0)]$, or $a_0 = \epsilon_0 h^2/\pi m e^2$. To go from SI to natural units in which $\hbar = c = 1$ (distinguished by a circumflex), use $Q = \hat{k}^{-1}\hat{Q}$, where $\hat{k}$ is the coefficient corresponding to Q in the third column. Thus $\hat{a}_0 = 4\pi\epsilon_0\hbar^2/[(\hat{m}\hbar/c)(\hat{e}^2\epsilon_0\hbar c)] = 4\pi/\hat{m}\hat{e}^2$. (In going *from* SI units, do not substitute for ϵ_0, μ_0, or c.)

Physical Quantity	Gaussian Units to SI	Natural Units to SI
Capacitance	$\alpha/4\pi\epsilon_0$	ϵ_0^{-1}
Charge	$(\alpha\beta/4\pi\epsilon_0)^{1/2}$	$(\epsilon_0\hbar c)^{-1/2}$
Charge density	$(\beta/4\pi\alpha^5\epsilon_0)^{1/2}$	$(\epsilon_0\hbar c)^{-1/2}$
Current	$(\alpha\beta/4\pi\epsilon_0)^{1/2}$	$(\mu_0/\hbar c)^{1/2}$
Current density	$(\beta/4\pi\alpha^3\epsilon_0)^{1/2}$	$(\mu_0/\hbar c)^{1/2}$
Electric field	$(4\pi\beta\epsilon_0/\alpha^3)^{1/2}$	$(\epsilon_0/\hbar c)^{1/2}$
Electric potential	$(4\pi\beta\epsilon_0/\alpha)^{1/2}$	$(\epsilon_0/\hbar c)^{1/2}$
Electric conductivity	$(4\pi\epsilon_0)^{-1}$	ϵ_0^{-1}
Energy	β	$(\hbar c)^{-1}$
Energy density	β/α^3	$(\hbar c)^{-1}$
Force	β/α	$(\hbar c)^{-1}$
Frequency	1	c^{-1}
Inductance	$4\pi\epsilon_0/\alpha$	μ_0^{-1}
Length	α	1
Magnetic induction	$(4\pi\beta/\alpha^3\mu_0)^{1/2}$	$(\mu_0\hbar c)^{-1/2}$
Magnetic intensity	$(4\pi\mu_0\beta/\alpha^3)^{1/2}$	$(\mu_0/\hbar c)^{1/2}$
Mass	β/α^2	$c/\hbar$
Momentum	β/α	$\hbar^{-1}$
Power	β	$(\hbar c^2)^{-1}$
Pressure	β/α^3	$(\hbar c)^{-1}$

(Continues)

Physical Quantity	Gaussian Units to SI	Natural Units to SI
Resistance	$4\pi\epsilon_0/\alpha$	$(\epsilon_0/\mu_0)^{1/2}$
Time	1	c
Velocity	α	c^{-1}

MAXWELL'S EQUATIONS

Name	Rationalized mks	Gaussian
Faraday's law	$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$	$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$
Ampere's law	$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}$	$\nabla \times \mathbf{H} = \frac{1}{c}\frac{\partial \mathbf{D}}{\partial t} + \frac{4\pi}{c}\mathbf{J}$
Poisson's equation	$\nabla \cdot \mathbf{D} = \rho$	$\nabla \cdot \mathbf{D} = 4\pi\rho$
[Absence of magnetic monopoles]	$\nabla \cdot \mathbf{B} = 0$	$\nabla \cdot \mathbf{B} = 0$
Lorentz force on charge q	$q[\mathbf{E} + \mathbf{v} \times \mathbf{B}]$	$q\left[\mathbf{E} + \frac{1}{c}\mathbf{v} \times \mathbf{B}\right]$
Constitutive relations	$\mathbf{D} = \epsilon\,\mathbf{E}$ $\mathbf{B} = \mu\mathbf{H}$	$\mathbf{D} = \epsilon\,\mathbf{E}$ $\mathbf{B} = \mu\mathbf{H}$

In a plasma, $\mu \approx \mu_o$ (Gaussian units: $\mu \approx 1$). The permittivity satisfies $\epsilon \approx \epsilon_0$ (Gaussian: $\epsilon \approx 1$) provided all charge is regarded as free. Using the drift approximation $\mathbf{v}_\perp = \mathbf{E} \times \mathbf{B}/B^2$ to calculate polarization charge density gives rise to a dielectric constant $K = \epsilon/\epsilon_0 = 1 + 36\pi \times 10^9\ \rho/B^2$ (mks) $= 1 + 4\pi\rho c^2/B^2$ (Gaussian), where ρ is the mass density.

Electromagnetic energy in volume V $$W = \frac{1}{2}\int_V dV(\mathbf{H} \cdot \mathbf{B} + \mathbf{E} \cdot \mathbf{D}) \qquad \text{(mks)}$$

$$= \frac{1}{8\pi}\int_V dV(\mathbf{H} \cdot \mathbf{B} + \mathbf{E} \cdot \mathbf{D}) \qquad \text{(cgs)}$$

Poynting's theorem $$\frac{\partial W}{\partial t} + \int_S \mathbf{N} \cdot d\mathbf{S} = -\int_V dV\,\mathbf{J} \cdot \mathbf{E},$$

where S is the closed surface bounding V and the Poynting vector (energy flux across S) is $\mathbf{N} = \mathbf{E} \times \mathbf{H}$ (mks) and $\mathbf{N} = c\mathbf{E} \times \mathbf{B}/4\pi$ (cgs).

ELECTRICITY AND MAGNETISM

In the following, ϵ = dielectric permittivity, μ = permeability of conductor, μ' = permeability of surrounding medium, σ = conductivity, $f = \omega/2\pi$ = radiation frequency, $\kappa_m = \mu/\mu_0$ and $\kappa_e = \epsilon/\epsilon_0$. Where subscripts are used, 1 denotes a conducting medium and 2 a propagating (lossless dielectric) medium. All units are mks unless otherwise specified.

Permittivity of free space	$\epsilon_0 = 8.8542 \times 10^{-12}$ farad/m.
Permeability of free space	$\mu_0 = 4\pi \times 10^{-7} = 1.2566 \times 10^{-6}$ henry/m.
Resistance of free space	$R_0 = (\mu_0/\epsilon_0)^{1/2} = 376.73$ ohm
Capacity of parallel plates of area A, separated by distance d	$C = \epsilon A/d$
Capacity of concentric cylinders of length l, radii a, b	$C = 2\pi\epsilon l/\ln(b/a)$
Capacity of concentric spheres of radii a, b	$C = 4\pi\epsilon ab/(b-a)$
Self-inductance of wire of length l, carrying uniform current	$L = \mu l$
Mutual inductance of parallel wires of length l, radius a, separated by distance d	$L = \dfrac{\mu' l}{4\pi}\left[1 + 4\ln\left(\dfrac{d}{a}\right)\right]$
Inductance of circular loop of radius b, made of wire of radius a, carrying uniform current	$L = b\{\mu'[\ln(8b/a)-2] + \mu/4\}$
Relaxation time in a lossy medium	$\tau = \epsilon/\sigma$
Skin depth in a lossy medium	$\delta = (2/\omega\mu\sigma)^{1/2} = (\pi f\mu\sigma)^{-1/2}$
Wave impedance in lossy medium	$Z = [\mu/(\epsilon + i\sigma/\omega)]^{1/2}$
Transmission coefficient at conducting surface (good only for $T << 1$)[8]	$T = 4.22 \times 10^{-4}\,(f\kappa_{m1}\kappa_{e2}/\sigma)^{1/2}$
Field at distance r from straight wire carrying current I (amperes)	$B_\theta = \mu I/2\pi r$ tesla $= 0.2I/r$ gauss (r in cm)
Field at distance z along axis from circular loop of radius a carrying current I	$B_z = \dfrac{\mu a^2 I}{2(a^2+z^2)^{3/2}}$

ELECTROMAGNETIC FREQUENCY/WAVELENGTH BANDS[9]

Designation	Frequency Range		Wavelength Range	
	Lower	Upper	Lower	Upper
ULF*		10 Hz	3 Mm	
ELF*	10 Hz	3 kHz	100 km	3 Mm
VLF	3 kHz	30 kHz	10 km	100 km
LF	30 kHz	300 kHz	1 km	10 km
MF	300 kHz	3 MHz	100 m	1 km
HF	3 MHz	30 MHz	10 m	100 m
VHF	30 MHz	300 MHz	1 m	10 m
UHF	300 MHz	3 GHz	10 cm	1 m
SHF†	3 GHz	30 GHz	1 cm	10 cm
S	2.6	3.95	7.6	11.5
G	3.95	5.85	5.1	7.6
J	5.3	8.2	3.7	5.7
H	7.05	10.0	3.0	4.25
X	8.2	12.4	2.4	3.7
M	10.0	15.0	2.0	3.0
P	12.4	18.0	1.67	2.4
K	18.0	26.5	1.1	1.67
R	26.5	40.0	0.75	1.1
EHF	30 GHz	300 GHz	1 mm	1 cm
(Submillimeter)	300 GHz	3 THz	100 μm	1 mm
(Infrared)	3 THz	430 THz	0.7 μm	100 μm
(Visible)	430 THz	750 THz	0.4 μm	0.7 μm
(Ultraviolet)	750 THz	30 PHz	10 nm	0.4 μm
(X Ray)	30 PHz	3 EHz	0.1 nm	10 nm
(Gamma Ray)	3 EHz			0.1 nm

Note In spectroscopy the angstrom (Å) is sometimes used (1 Å = 10^{-8} cm = 0.1 nm)
*The boundary between ULF and ELF is variously defined.
†The SHF (microwave) band is further subdivided approximately as shown.[10]

AC CIRCUITS

For a resistance R, inductance L, and capacitance C in series with a voltage source $V = V_0 \exp(j\omega t)$ (here $j = \sqrt{-1}$), the current $I = dq/dt$, where q satisfies

$$L \frac{d^2q}{dt^2} + R\frac{dq}{dt} + q/C = V.$$

Solutions are $q(t) = q_s + q_t$, $I(t) = I_s + I_t$, where the steady state is $I_s = j\omega q_s = V/Z$ in terms of the impedance $Z = R + j(\omega L - 1/\omega C)$ and $I_t = dq_t/dt$. For initial conditions $q(0) = q_0 = \bar{q}_0 + q_s$, $I(0) = I_0$, the transients can be of three types, depending on $\Delta = R^2 - 4L/C$:

(a) Overdamped, $\Delta > 0$

$$q_t = [(I_0 + \gamma_+\bar{q}_0)e^{-\gamma_- t} - (I_0 + \gamma_-\bar{q}_0)e^{-\gamma_+ t}]/(\gamma_+ - \gamma_-);$$

$$I_t = [\gamma_+(I_0 + \gamma_-\bar{q}_0)e^{-\gamma_+ t} - \gamma_-(I_0 + \gamma_+\bar{q}_0)e^{-\gamma_- t}]/(\gamma_+ - \gamma_-),$$

where $\gamma_\pm = (R \pm \Delta^{1/2})/2L$;

(b) Critically damped, $\Delta = 0$

$$q_t = [\bar{q}_0 + (I_0 + \gamma_R\bar{q}_0)t]e^{-\gamma_R t};$$

$$I_t = [I_0 - (I_0 + \gamma_R\bar{q}_0)\gamma_R t]e^{-\gamma_R t},$$

where $\gamma_R = R/2L$;

(c) Underdamped, $\Delta < 0$

$$q_t = [\omega_1^{-1}(\gamma_R\bar{q}_0 + I_0)\sin\omega_1 t + \bar{q}_0\cos\omega_1 t]e^{-\gamma_R t};$$

$$I_t = \{I_0\cos\omega_1 t - [(\omega_1 + \gamma_R^2/\omega_1)\bar{q}_0 + (\gamma_R/\omega_1)I_0]\sin(\omega_1 t)\}e^{-\gamma_R t},$$

where $\omega_1 = \omega_0(1 - R^2C/4L)^{1/2}$, $\omega_0 = (LC)^{-1/2}$. The quality of the circuit is $Q = \omega_0 L/R$; ω_0 is the resonant frequency. At $\omega = \omega_0$, $Z = R$. Instability results when L, R, C are not all of the same sign.

DIMENSIONLESS NUMBERS OF FLUID MECHANICS[11]

Name(s)	Symbol	Definition	Significance
Alfvén/Kármán	Al/Ka	$^*V_A/V$	(Magnetic force/inertial forces)$^{1/2}$
Bond	Bd	$(\rho' - \rho)L^2g/\Sigma$	Gravitational force/surface tension
Boussinesq	B	$V/(2gR)^{1/2}$	(Inertial force/gravitational force)$^{1/2}$
Brinkman	Br	$\mu V^2/k\Delta T$	Viscous heat/conducted heat
Capillary	Cp	$\mu V/\Sigma$	Viscous force/surface tension
Carnot	Ca	$(T_2 - T_1)/T_2$	Theoretical Carnot cycle efficiency
Cauchy/Hooke	Cy/Hk	$\rho V^2/\Gamma = M^2$	Inertial force/compressibility force
Clausius	Cl	$LV^3\rho/k\Delta T$	Kinetic energy flow rate/heat conduction rate
Cowling	C	$(V_A/V)^2 = Al^2$	Magnetic force/inertial forces
Crispation	Cr	$\mu\kappa/\Sigma L$	Effect of diffusion/effect of surface tension
Dean	D	$(DV/\nu)(D/2r)^{1/2}$	Transverse flow due to curvature/ longitudinal flow
(Drag coefficient)	C_D	$(\rho' - \rho)Lg/\rho' V^2$	Drag force/inertial forces
Eckert	E	$V^2/c_p\Delta T$	Kinetic energy/change in thermal energy
Ekman	Ek	$(\nu/2\Omega L^2)^{1/2} = (Ro/Re)^{1/2}$	(Viscous force/Coriolis force)$^{1/2}$
Euler	Eu	$\Delta p/\rho V^2$	Pressure drop due to friction/ kinetic energy density
Froude	Fr	$^\dagger V/(gL)^{1/2}$ V/NL	(Inertial forces/gravitational or buoyancy forces)$^{1/2}$
Gay-Lussac	Ga	$1/\beta\Delta T$	(Relative volume change during heating)$^{-1}$
Grashof	Gr	$gL^3\beta\Delta T/\nu^2$	Buoyancy force/viscous force
(Hall coefficient)	C_H	λ/r_L	Gyrofrequency/collision frequency
Hartmann	H	$BL/(\mu\eta)^{1/2} = (Rm\ Re\ C)^{1/2}$	Magnetic force/dissipative forces
Knudsen	Kn	λ/L	Hydrodynamic time/collision time
Lorentz	Lo	V/c	Magnitude of relativistic effects
Lundquist	Lu	$LV_A\mu_0/\eta = Al\ Rm$	$\mathbf{J} \times \mathbf{B}$ force/resistive magnetic diffusion force

Name(s)	Symbol	Definition	Significance
Mach	M	V/C_s	Magnitude of compressibility effects
Magnetic Mach	Mm	$V/V_A = A\Gamma^{-1}$	(Inertial force/magnetic force)$^{1/2}$
Magnetic Reynolds	Rm	$\mu_0 LV/\eta$	Flow velocity/magnetic diffusion velocity
Newton	Nt	$F/\rho L^2 V^2$	Imposed force/inertial forces
Nusselt	N	$\alpha L/k$	Total heat transfer/thermal conduction
Péclet	Pe	LV/κ	Heat convection/heat conduction
Poisseuille	Po	$D^2\Delta p/\mu LV$	Pressure force/viscous force
Prandtl/Schmidt	Pr/Sc	ν/κ	Momentum diffusion/heat diffusion
Rayleigh	Ra	$gH^3\beta\Delta T/\nu\kappa$	Buoyancy force/diffusion forces
Reynolds	Re	LV/ν	Inertial forces/viscous force
Richardson	Ri	$(NH/\Delta V)^2$	Buoyancy effects/vertical shear effects
Rossby	Ro	$V/2\Omega L \sin \Lambda$	Inertial force/Coriolis force
Taylor	Ta	$\Omega R^{1/2}(\Delta R)^{3/2}/\nu$ $(2\Omega L^2/\nu)^2$	(Centrifugal force/viscous force)$^{1/2}$ Centrifugal force/viscous force
Thring/ Boltzmann	Th/Bo	$\rho c_p V/\epsilon\sigma T^3$	Convective heat transport/ radiative heat transport
Stanton	St	$\alpha/\rho c_p V$	Thermal conduction loss/ heat capacity
Stefan	Sf	$\sigma LT^3/k$	Radiated heat/conducted heat
Stokes	S	$\nu/L^2 f$	Viscous damping rate/vibration frequency
Strouhal	Sr	fL/V	Vibration speed/flow velocity
Weber	W	$\rho LV^2/\Sigma$	Inertial force/surface tension

*(†) Also defined as the inverse (square) of the quantity shown.

Nomenclature:

B	Magnetic induction
C_s, c	Speeds of sound, light
c_p	Specific heat at constant pressure (units ℓ^2/t^2-deg)
$D = 2R$	Pipe diameter

F	Imposed force
f	Vibration frequency
g	Gravitational acceleration
H, L	Vertical, horizontal scale lengths
$k = \rho c_p \kappa$	Thermal conductivity (units $m/\ell t^2$)
$N = (g/H)^{1/2}$	Brunt-Väisälä frequency
R	Radius of pipe or channel
r	Radius of curvature of pipe or channel
r_L	Larmor radius
T	Temperature
V	Characteristic flow velocity
$V_A = B/(\mu_0 \rho)^{1/2}$	Alfvén speed
α	Newton's-law heat coefficient, $k \dfrac{\partial T}{\partial x} = \alpha \Delta T$
β	Volumetric expansion coefficient, $dV/V = \beta dT$
Γ	Bulk modulus (units $m/\ell t^2$)
ΔR, ΔV, Δp, ΔT	Imposed difference in two radii, velocities, pressures, or temperatures
ϵ	Surface emissivity
η	Electrical resistivity
κ	Thermal diffusivity (units ℓ^2/t)
Λ	Latitude of position on earth's surface
λ	Collisional mean free path
$\mu = \rho \nu$	Bulk viscosity
$\mu_0 = 4\pi \times 10^{-7}$ H m^{-1}	Permeability of free space
ν	Kinematic viscosity (units ℓ^2/t)
ρ	Mass density of fluid medium
ρ'	Mass density of bubble, droplet, or moving object
Σ	Surface tension (units m/t^2)
σ	Stefan-Boltzmann coefficient
Ω	Solid body rotational angular velocity

SHOCKS

At a shock front $\mathscr{S}$ propagating in a magnetized fluid at an angle θ with respect to the magnetic induction $\mathbf{B}$, the jump conditions are[12, 13]

(1) $\rho U = \bar{\rho}\bar{U} \equiv q$;

(2) $\rho U^2 + p + B_\perp^2/2\mu = \bar{\rho}\bar{U}^2 + \bar{p} + \bar{B}_\perp^2/2\mu$;

(3) $\rho UV - B_\parallel B_\perp/\mu = \bar{\rho}\bar{U}\bar{V} - \bar{B}_\parallel \bar{B}_\perp/\mu$;

(4) $B_\parallel = \bar{B}_\parallel$;

(5) $UB_\perp - VB_\parallel = \bar{U}\bar{B}_\perp - \bar{V}\bar{B}_\parallel$;

(6) $$\frac{1}{2}(U^2 + V^2) + w + (UB_\perp^2 - VB_\parallel B_\perp)/\mu\rho U$$
$$= \frac{1}{2}(\bar{U}^2 + \bar{V}^2) + \bar{w} + (\bar{U}\bar{B}_\perp^2 - \bar{V}\bar{B}_\parallel \bar{B}_\perp)/\mu\bar{\rho}\bar{U}.$$

Here U and V are components of the fluid velocity normal and tangential to $\mathscr{S}$ in the shock frame; $\rho = 1/v$ is the mass density; p is the pressure; $B_\perp = B\sin\theta$, $B_\parallel = B\cos\theta$; μ is the magnetic permeability ($\mu = 4\pi$ in cgs units); and the specific enthalpy is $w = e + pv$, where the specific internal energy e satisfies $de = Tds - pdv$ in terms of the temperature T and specific entropy s. Quantities in the region behind (downstream from) $\mathscr{S}$ are distinguished by a bar. If $\mathbf{B} = 0$, then[14]

(7) $U - \bar{U} = [(\bar{p} - p)(v - \bar{v})]^{1/2}$;

(8) $(\bar{p} - p)(v - \bar{v}) = q^2$;

(9) $\bar{w} - w = \frac{1}{2}(\bar{p} - p)(v + \bar{v})$;

(10) $\bar{e} - e = \frac{1}{2}(\bar{p} + p)(v - \bar{v})$.

In what follows we assume the fluid is a perfect gas with adiabatic index $\gamma = 1 + 2/n$, where n is the number of degrees of freedom. Then $p = \rho RT/m$, where R is the universal gas constant and m is the molar weight; the sound speed is given by $C_s^2 = (\partial p/\partial \rho)_s = \gamma pv$; and $w = \gamma e = \gamma pv/(\gamma + 1)$. For a general oblique shock in a perfect gas the quantity $X = (U/V_A)^2/r$ satisfies[13]

(11) $(X - \beta/\alpha)(X - \cos^2\theta)^2 = X\sin^2\theta\{[1 + (r-1)/2\alpha]X - \cos^2\theta\}$,

where $r = \bar{\rho}/\rho$, $\alpha = \frac{1}{2}[\gamma + 1 - (\gamma - 1)r]$, and $\beta = C_s^2/V_A^2 = 4\pi\gamma p/B^2$. The density ratio is bounded by

(12) $1 < r < (\gamma + 1)/(\gamma - 1)$.

If the shock is normal to **B** ($\theta = \pi/2$), then

(13) $U^2 = r\{C_s^2 + V_A^2[1 + (1 - \gamma/2)(r - 1]\}/\alpha;$

(14) $U/\bar{U} = \bar{B}/B = r;$

(15) $\bar{V} = V;$

(16) $\bar{p} = p + (1 - 1/r)\rho U^2 + (1 - r^2)B^2/2\mu.$

If $\theta = 0$, there are two possibilities: switch-on shocks, which require $\beta < 1$ and for which

(17) $U^2 = rV_A^2;$

(18) $\bar{U} = V_A^2/U;$

(19) $\bar{B}_\perp^2 = 2B_\parallel^2(r - 1)(\alpha - \beta);$

(20) $\bar{V} = \bar{U}\,\bar{B}_\perp/B_\parallel;$

(21) $\bar{p} = p + \rho U^2(1 - \alpha + \beta)(1 - 1/r).$

and acoustic (hydrodynamic) shocks, for which

(22) $U^2 = rC_s^2/\alpha;$

(23) $\bar{U} = U/r;$

(24) $\bar{V} = \bar{B}_\perp = 0;$

(25) $\bar{p} = p + \rho U^2(1 - 1/r).$

For acoustic shocks the specific volume and pressure are related by

(26) $\bar{v}/v = [(\gamma + 1)p + (\gamma - 1)\bar{p}]/[(\gamma - 1)p + (\gamma + 1)\bar{p}].$

In terms of the incident Mach number $M = U/C_s$,

(27) $\bar{\rho}/\rho = v/\bar{v} = U/\bar{U} = (\gamma + 1)M^2/[(\gamma - 1)M^2 + 2];$

(28) $\bar{p}/p = (2\gamma M^2 - \gamma + 1)/(\gamma + 1);$

(29) $\bar{T}/T = [(\gamma - 1)M^2 + 2](2\gamma M^2 - \gamma + 1)/(\gamma + 1)^2M^2;$

(30) $\bar{M}^2 = [(\gamma - 1)M^2 + 2]/[2\gamma M^2 - \gamma + 1].$

The entropy change across the shock is

(31) $\Delta s = \bar{s} - s = c_v \ln[(\bar{p}/p)(\rho/\bar{\rho})^\gamma],$

where $c_v = R/(\gamma - 1)m$ is the specific heat at constant volume. In the weak shock limit ($M \to 1$),

(36) $$\Delta s \to c_v \frac{2\gamma(\gamma - 1)}{3(\gamma + 1)}(M^2 - 1)^3 \approx \frac{16\gamma R}{3(\gamma + 1)m}(M - 1)^3.$$

FUNDAMENTAL PLASMA PARAMETERS

All quantities are in Gaussian units except temperature (T_e, T_i, T) expressed in eV and ion mass (m_i) expressed in units of proton mass, $\mu = m_i/m_p$; Z is charge state; k is Boltzmann's constant; K is wavelength; γ is the adiabatic index; $\ln \Lambda$ is the Coulomb logarithm.

Frequencies

electron gyrofrequency	$f_{ce} = \omega_{ce}/2\pi = 2.80 \times 10^6 B$ Hz
	$\omega_{ce} = eB/m_e c = 1.76 \times 10^7 B$ rad/sec
ion gyrofrequency	$f_{ci} = \omega_{ci}/2\pi = 1.52 \times 10^3 Z\mu^{-1} B$ Hz
	$\omega_{ci} = eB/m_i c = 9.58 \times 10^3 Z\mu^{-1} B$ rad/sec
electron plasma frequency	$f_{pe} = \omega_{pe}/2\pi = 8.98 \times 10^3 n_e^{1/2}$ Hz
	$\omega_{pe} = (4\pi n_e e^2/m_e)^{1/2}$
	$= 5.64 \times 10^4 n_e^{1/2}$ rad/sec
ion plasma frequency	$f_{pi} = \omega_{pi}/2\pi = 2.10 \times 10^2 Z\mu^{-1/2} n_i^{1/2}$ Hz
	$\omega_{pi} = (4\pi n_i Z^2 e^2/m_i)^{1/2} = 1.32 \times 10^3 Z\mu^{-1/2} n_i^{1/2}$ rad/sec
electron trapping rate	$\nu_{Te} = \left(\frac{eKE}{m_e}\right)^{1/2} = 7.26 \times 10^8 K^{1/2} E^{1/2}$ sec^{-1}
ion trapping rate	$\nu_{Ti} = \left(\frac{eKE}{m_i}\right)^{1/2} = 1.69 \times 10^7 K^{1/2} E^{1/2} \mu^{-1/2}$ sec^{-1}
electron collision rate	$\nu_e = 2.91 \times 10^{-6} n_e \ln \Lambda \; T_e^{-3/2}$ sec^{-1}
ion collision rate	$\nu_i = 4.78 \times 10^{-8} n_i Z^2 \ln \Lambda \; T_i^{-3/2}$ sec^{-1}

Lengths

electron deBroglie length	$\lambda\!\!\!^{-} = \hbar/(m_e k T_e)^{1/2} = 2.76 \times 10^{-8} T_e^{-1/2}$ cm
classical distance of minimum approach	$e^2/kT = 1.44 \times 10^{-7} T^{-1}$ cm
electron gyroradius	$r_e = v_{Te}/\omega_{ce} = 2.38 \, T_e^{1/2} B^{-1}$ cm
ion gyroradius	$r_i = v_{Ti}/\omega_{ci} = 1.02 \times 10^2 \mu^{1/2} Z^{-1} T_i^{1/2} B^{-1}$ cm
plasma skin depth	$c/\omega_{pe} = 5.31 \times 10^5 n^{-1/2}$ cm
Debye length	$\lambda_D = (kT/4\pi n e^2)^{1/2} = 7.43 \times 10^2 T^{1/2} n^{-1/2}$ cm

Velocities

electron thermal velocity	$v_{Te} = (kT_e/m_e)^{1/2} = 4.19 \times 10^7\ T_e^{1/2}$ cm/sec
ion thermal velocity	$v_{Ti} = (kT_i/m_i)^{1/2} = 9.79 \times 10^5\ \mu^{-1/2} T_i^{1/2}$ cm/sec
ion sound velocity	$c_s = (\gamma Z k T_e/m_i)^{1/2} = 9.79 \times 10^5 (\gamma Z T_e/\mu)^{1/2}$ cm/sec
Alfvén velocity	$v_A = B/(4\pi n_i m_i)^{1/2}$ $= 2.18 \times 10^{11}\ \mu^{-1/2} n_i^{-1/2} B$ cm/sec

Dimensionless

(electron/proton mass ratio)$^{1/2}$	$(m_e/m_p)^{1/2} = 2.33 \times 10^{-2} = 1/42.9$
number of particles in Debye sphere	$\frac{4\pi}{3} n \lambda_D^3 = 1.72 \times 10^9\ T^{3/2} n^{-1/2}$
Alfvén velocity/speed of light	$v_A/c = 7.28\ \mu^{-1/2} n_i^{-1/2} B$
magnetic/ion rest energy ratio	$B^2/8\pi n_i m_i c^2 = 26.5\ \mu^{-1} n_i^{-1} B^2$
electron plasma/gyrofrequency ratio	$\omega_{pe}/\omega_{ce} = 3.21 \times 10^{-3}\ n_e^{1/2} B^{-1}$
ion plasma/gyrofrequency ratio	$\omega_{pi}/\omega_{ci} = 0.137\ \mu^{1/2} n_i^{1/2} B^{-1}$
thermal/magnetic energy ratio	$\beta = 8\pi n k T/B^2 = 4.03 \times 10^{-11}\ n T B^{-2}$

Miscellaneous

Bohm diffusion coefficient	$D_B = \dfrac{ckT}{16\,eB} = 6.25 \times 10^6\ T B^{-1}$ cm^2/sec
Transverse Spitzer resistivity	$\eta_\perp = 1.15 \times 10^{-14}\ Z \ln \Lambda\ T^{-3/2}$ sec $= 1.03 \times 10^{-2}\ Z \ln \Lambda\ T^{-3/2}$ ohm–cm

The anomalous collision rate due to low frequency ion sound turbulence is

$$\nu^* \approx \omega_{pe} W/kT = 5.64 \times 10^4\ n^{-1/2}\ W/kT\ \text{sec}^{-1},$$

where W is the total energy of waves with $\omega/K < v_{Ti}$.

Magnetic presure is given by

$$P = B^2/8\pi = 3.98 \times 10^6 B^2 \text{ dynes/cm}^2$$
$$= 3.93 (B/B_0)^2 \text{ atm},$$

where $B_0 = 10$ kG $= 1$ T.

Energy of detonation of 1 kiloton of high explosive is

$$W_{kT} = 10^{12} \text{ cal} = 4.2 \times 10^{19} \text{ erg}.$$

PLASMA DISPERSION FUNCTION

Definition (first form valid only for $Im\ \zeta > 0$)

$$Z(\zeta) = \pi^{-1/2}\int_{-\infty}^{\infty} \frac{dt\ e^{-t^2}}{t-\zeta} = 2ie^{-\zeta^2} \int_{-\infty}^{i\zeta} dt\ e^{-t^2}.$$

Physically $\zeta = x + iy$ is the ratio of phase to thermal velocity.[15]

Differential equation

$$\frac{dZ}{d\zeta} = -2[1 + \zeta Z],\ Z(0) = i\pi^{1/2}; \qquad \frac{d^2Z}{d\zeta^2} + 2\zeta\frac{dZ}{d\zeta} + 2Z = 0.$$

Real argument ($y = 0$)

$$Z(x) = e^{-x^2}\left[i\pi^{1/2} - 2\int_0^x dt\, e^{t^2}\right]$$

Imaginary argument ($x = 0$)

$$Z(iy) = i\pi^{1/2} \exp(y^2)\ [1 - \mathrm{erf}(y)].$$

Power series (small argument)

$$Z(\zeta) = i\pi^{1/2} \exp(-\zeta^2) - 2\zeta[1 - 2\zeta^2/3 + 4\zeta^4/15 - 8\zeta^6/105 + \ldots].$$

Asymptotic series ($|\zeta| >> 1$)[16]

$$Z(\zeta) = i\pi^{1/2}\sigma \exp(-\zeta^2) - \zeta^{-1}[1 + 1/2\zeta^2 + 3/4\zeta^4 + 15/8\zeta^6 + \ldots].$$

$$\sigma = \begin{cases} 0 & y > 1/|x| \\ 1 & |y| < 1/|x| \\ 2 & -y > 1/|x| \end{cases}$$

Symmetry properties ($\zeta^* = x - iy$)

$$Z(\zeta^*) = -[Z(-\zeta)]^*$$

$$Z(x - iy) = [Z(x + iy)]^* + 2i\pi^{1/2}\exp[-(x - iy)^2] \quad (y > 0).$$

Two-pole approximations for ζ in upper half plane (good except when $y < \pi^{1/2} x^3 e^{-x^2}$, $x >> 1$)[17]

$$Z(\zeta) \approx \frac{0.50 + 0.81\,i}{a - \zeta} - \frac{0.50 - 0.81\,i}{a^* + \zeta}, \quad a = 0.51 - 0.81\,i;$$

$$Z'(\zeta) \approx \frac{0.50 + 0.96\,i}{(b - \zeta)^2} + \frac{0.50 - 0.96\,i}{(b^* + \zeta)^2}, \quad b = 0.48 - 0.91\,i.$$

COLLISIONS AND TRANSPORT

Temperatures are in eV; the corresponding value of Boltzmann's constant is $k = 1.60 \times 10^{-12}$ erg/eV; masses μ, μ' are in units of the proton mass; $e_\alpha = Z_\alpha e$ is the charge of species α. All other units are cgs except where noted.

Relaxation Rates

Rates are associated with four relaxation processes arising from the interaction of test particles (labeled α) streaming through a background of field particles (labeled β):

slowing down	$\dfrac{d\mathbf{v}_\alpha}{dt} = -\nu_s^{\alpha/\beta}\mathbf{v}_\alpha;$
transverse diffusion	$\dfrac{d}{dt}(\mathbf{v}_\alpha - \bar{\mathbf{v}}_\alpha)_\perp^2 = \nu_\perp^{\alpha/\beta} v_\alpha^2;$
parallel diffusion	$\dfrac{d}{dt}(\mathbf{v}_\alpha - \bar{\mathbf{v}}_\alpha)_\parallel^2 = \nu_\parallel^{\alpha/\beta} v_\alpha^2,$
energy loss	$\dfrac{d}{dt} v_\alpha^2 = -\nu_\epsilon^{\alpha/\beta} v_\alpha^2,$

where the averages are performed over an ensemble of test particles and a Maxwellian field particle distribution. The exact formulas may be written[18]

$$\nu_s^{\alpha/\beta} = (1 + m_\alpha/m_\beta)\psi(x^{\alpha/\beta})\,\nu_0^{\alpha/\beta}\ \text{sec}^{-1};$$

$$\nu_\perp^{\alpha/\beta} = 2[\psi(x^{\alpha/\beta})(1 - 1/2x^{\alpha/\beta}) + \psi'(x^{\alpha/\beta})]\,\nu_0^{\alpha/\beta}\ \text{sec}^{-1};$$

$$\nu_\parallel^{\alpha/\beta} = [\psi(x^{\alpha/\beta})/x^{\alpha/\beta}]\,\nu_0^{\alpha/\beta}\ \text{sec}^{-1};$$

$$\nu_\epsilon^{\alpha/\beta} = 2[(m_\alpha/m_\beta)\psi(x^{\alpha/\beta}) - \psi'(x^{\alpha/\beta})]\,\nu_0^{\alpha/\beta}\ \text{sec}^{-1},$$

where

$$\nu_0^{\alpha/\beta} = 4\pi e_\alpha^2 e_\beta^2 \lambda_{\alpha\beta} n_\beta / m_\alpha^2 v_\alpha^3\ \text{sec}^{-1}; \qquad x^{\alpha/\beta} = m_\beta v_\alpha^2/2kT_\beta;$$

$$\psi(x) = \frac{2}{\sqrt{\pi}}\int_0^x dt\sqrt{t}\,e^{-t}; \qquad \psi'(x) = \frac{d\psi}{dx},$$

and $\lambda_{\alpha\beta} = \ln\ \Lambda_{\alpha\beta}$ is the Coulomb logarithm (see below). Limiting forms of ν_s, $\nu_\perp$ and $\nu_\parallel$ are given in the following table. All the expressions shown have units cm^3/sec. Test particle energy ϵ and field particle temperature T are both in eV; $\mu = m_i/m_p$, where m_p is the proton mass; Z is ion charge state; for electron-electron and ion-ion encounters, field particle quantities are distinguished by a prime. The two expressions given for each rate hold for very slow ($x^{\alpha/\beta} << 1$) and very fast ($x^{\alpha/\beta} >> 1$) test particles, respectively.

Electron-electron	Slow	Fast
$\nu_s^{e/e'}/n_{e'}\lambda_{ee'}$	$\approx 5.8\times10^{-6}\,T^{-3/2}$	$\longrightarrow 7.7\times10^{-6}\,\epsilon^{-3/2}$
$\nu_\perp^{e/e'}/n_{e'}\lambda_{ee'}$	$\approx 5.8\times10^{-6}\,T^{-1/2}\,\epsilon^{-1}$	$\longrightarrow 7.7\times10^{-6}\,\epsilon^{-3/2}$
$\nu_{\parallel}^{e/e'}/n_{e'}\lambda_{ee'}$	$\approx 2.9\times10^{-6}\,T^{-1/2}\,\epsilon^{-1}$	$\longrightarrow 3.9\times10^{-6}\,T\epsilon^{-5/2}$
Electron-ion		
$\nu_s^{e/i}/n_iZ^2\lambda_{ei}$	$\approx 0.23\,\mu^{3/2}\,T^{-3/2}$	$\longrightarrow 3.9\times10^{-6}\,\epsilon^{-3/2}$
$\nu_\perp^{e/i}/n_iZ^2\lambda_{ie}$	$\approx 2.5\times10^{-4}\,\mu^{1/2}\,T^{-1/2}\,\epsilon^{-1}$	$\longrightarrow 7.7\times10^{-6}\,\epsilon^{-3/2}$
$\nu_{\parallel}^{e/i}/n_iZ^2\lambda_{ie}$	$\approx 1.2\times10^{-4}\,\mu^{1/2}\,T^{-1/2}\,\epsilon^{-1}$	$\longrightarrow 2.1\times10^{-9}\,\mu^{-1}\,T\epsilon^{-5/2}$
Ion-electron		
$\nu_s^{i/e}/n_eZ^2\lambda_{ie}$	$\approx 1.6\times10^{-9}\,\mu^{-1}\,T^{-3/2}$	$\longrightarrow 1.7\times10^{-4}\,\mu^{1/2}\,\epsilon^{-3/2}$
$\nu_\perp^{i/e}/n_eZ^2\lambda_{ie}$	$\approx 3.2\times10^{-9}\,\mu^{-1}\,T^{-1/2}\,\epsilon^{-1}$	$\longrightarrow 1.8\times10^{-7}\,\mu^{-1/2}\,\epsilon^{-3/2}$
$\nu_{\parallel}^{i/e}/n_eZ^2\lambda_{ie}$	$\approx 1.6\times10^{-9}\,\mu^{-1}\,T^{-1/2}\,\epsilon^{-1}$	$\longrightarrow 1.7\times10^{-4}\,\mu^{1/2}\,T\epsilon^{-5/2}$
Ion-ion		
$\nu_s^{i/i'}/n_{i'}Z^2Z'^2\lambda_{ii'}$	$\approx 6.8\times10^{-8}\dfrac{\mu'^{1/2}}{\mu}\left(1+\dfrac{\mu'}{\mu}\right)T^{-3/2}$	$\longrightarrow 9.0\times10^{-8}\,\mu^{-1/2}\left(1+\dfrac{\mu}{\mu'}\right)\epsilon^{-3/2}$
$\nu_\perp^{i/i'}/n_{i'}Z^2Z'^2\lambda_{ii'}$	$\approx 1.4\times10^{-7}\,\mu'^{1/2}\,\mu^{-1}\,T^{-1/2}\epsilon^{-1}$	$\longrightarrow 1.8\times10^{-7}\,\mu^{-1/2}\,\epsilon^{-3/2}$
$\nu_{\parallel}^{i/i'}/n_{i'}Z^2Z'^2\lambda_{ii'}$	$\approx 6.8\times10^{-8}\,\mu'^{1/2}\,\mu^{-1}\,T^{-1/2}\epsilon^{-1}$	$\longrightarrow 9.0\times10^{-8}\,\mu^{1/2}\,\mu'^{-1}\,T\epsilon^{-5/2}$

In the same limits, the energy transfer rate follows from the identity

$$\nu_\epsilon = 2\,\nu_s - \nu_\perp - \nu_{\parallel}\ ,$$

except for the case of fast electrons or fast ions scattered by ions, where the leading terms cancel. Here the appropriate forms are

$$\nu_\epsilon^{e/i} \longrightarrow 4.2\times10^{-9}\,n_iZ^2\lambda_{ei}\left[\epsilon^{-3/2}\mu^{-1} - 8.9\times10^4\,(\mu/T)^{1/2}\,\epsilon^{-1}\exp(-1836\,\mu\epsilon/T)\right]\ \mathrm{sec}^{-1}$$

and

$$\nu_\epsilon^{i/i'} \longrightarrow 1.8\times10^{-7}\,n_{i'}Z^2Z'^2\lambda_{ii'}\left[\epsilon^{-3/2}\mu^{1/2}/\mu' - 1.1\,(\mu'/T)^{1/2}\epsilon^{-1}\exp(-\mu'\epsilon/T)\right]\ \mathrm{sec}^{-1}.$$

In general, the energy transfer rate $\nu_\epsilon^{\alpha/\beta}$ is positive for $\epsilon > \epsilon_\alpha{}^*$ and negative for $\epsilon < \epsilon_\alpha{}^*$, where $x^* = (m_\beta/m_\alpha)\ \epsilon_\alpha{}^*/T_\beta$ is the solution of $m_\beta/m_\alpha = \psi(x^*)/\psi'(x^*)$.

The ratio $\epsilon_\alpha^*/T_\beta$ is given for a number of specific α, β in the following table:

α/β	i/e	e/e	i/i	e/p	e/D	e/T, e/He^3	e/He^4
$\dfrac{\epsilon_\alpha^*}{kT_\beta}$	1.5	.98	.98	4.8×10^{-3}	2.6×10^{-3}	1.8×10^{-3}	1.4×10^{-3}

When both species are near Maxwellian with $T_i \lesssim T_e$, there are just two characteristic collision rates. For $Z = 1$,

$$\nu_e = 2.9 \times 10^{-6}\, n\lambda T_e^{-3/2}\ \mathrm{sec}^{-1},$$

$$\nu_i = 4.8 \times 10^{-8}\, n\lambda T_i^{-3/2}\mu^{-1/2}\ \mathrm{sec}^{-1}$$

Thermal Equilibration

If the components of a plasma have different temperatures, but no relative drift, equilibration is described by

$$dT_\alpha/dt = \sum_\beta \bar{\nu}_\epsilon^{\alpha/\beta}(T_\beta - T_\alpha),$$

where

$$\bar{\nu}_\epsilon^{\alpha/\beta} = 1.8 \times 10^{-19} \frac{(m_\alpha m_\beta)^{1/2} Z_\alpha^2 Z_\beta^2 n_\beta \lambda_{\alpha\beta}}{(m_\alpha T_\beta + m_\beta T_\alpha)^{3/2}}\ \mathrm{sec}^{-1}$$

For electrons and ions with $T_e \sim T_i = T$, this implies

$$\bar{\nu}_\epsilon^{e/i}/n_i = \bar{\nu}_\epsilon^{i/e}/n_e = 3.2 \times 10^{-9}\ Z^2\lambda/\mu T^{3/2}\ \mathrm{cm^3/sec}.$$

Temperature Anisotropy

Isotropization is described by

$$dT_\perp/dt = -(1/2)dT_{\parallel}/dt = -\nu_T^\alpha(T_\perp - T_{\parallel}),$$

where, if $A = T_\perp/T_{\parallel} - 1 > 0$,

$$\nu_T^\alpha = \frac{2\sqrt{\pi}e_\alpha^2 e_\beta^2 n_\alpha \lambda}{m_\alpha^{1/2}(kT_{\parallel})^{3/2}} A^{-2}\left[-3 + (A+3)\frac{\tan^{-1}A^{1/2}}{A^{1/2}}\right] \mathrm{sec}^{-1}.$$

if $A < 0$, $\tan^{-1}A^{1/2}/A^{1/2}$ is replaced by $\tanh^{-1}(-A)^{1/2}/(-A)^{1/2}$.

For $T_\perp = T_{\parallel} = T$,

$$\nu_T^e = 8.2 \times 10^{-7}\, n\lambda T^{-3/2}\ \mathrm{sec}^{-1};$$

$$\nu_T^i = 1.9 \times 10^{-8}\, n\lambda Z^2/\mu T^{3/2}\ \mathrm{sec}^{-1}.$$

Coulomb Logarithm

For test particles of mass m_α, charge $e_\alpha = Z_\alpha e$, scattering off field particles of mass m_β, charge $e_\beta = Z_\beta e$, the Coulomb logarithm is defined as $\lambda = \ln \Lambda = \ln(r_{max}/r_{min})$. Here r_{min} is the larger of $e_\alpha e_\beta/(m_{\alpha\beta}\bar{u}^2)$ and $\hbar/(2\, m_{\alpha\beta}\bar{u})$, averaged over both particle velocity distributions, where $m_{\alpha\beta} = m_\alpha m_\beta/(m_\alpha + m_\beta)$ and $\mathbf{u} = \mathbf{v}_\alpha - \mathbf{v}_\beta$; $r_{max} = (4\pi \Sigma n_\gamma e_\gamma^2/kT_\gamma)^{-1/2}$, where the summation extends over all species γ for which $\bar{u}^2 < v_{T\gamma}^2$, with $v_{T\gamma} = (kT_\gamma/m_\gamma)^{1/2}$. If this inequality cannot be satisfied or if either $\bar{u}\,\omega_{c\alpha}^{-1} < r_{max}$ or $\bar{u}\,\omega_{c\beta}^{-1} < r_{max}$, the theory breaks down. Typically $\lambda \approx 10 - 20$. Corrections to the transport coefficients are $O(\lambda^{-1})$, hence the theory is good only to $\sim 10\%$ and fails when $\lambda \sim 1$.

The following cases are of particular interest:

(a) Thermal electron-electron collisions

$$\lambda_{ee} = 23 - \ln(n_e^{1/2}T_e^{-3/2}) \qquad T_e \lesssim 10 \text{ eV}$$
$$= 24 - \ln(n_e^{1/2}T_e^{-1}) \qquad T_e \gtrsim 10 \text{ eV}$$

(b) Electron-ion collisions

$$\lambda_{ei} = \lambda_{ie} = 23 - \ln(n_e^{1/2} Z T_e^{-3/2}), \quad 10Z^2 \text{ eV} > T_e > T_i m_e/m_i;$$
$$= 24 - \ln(n_e^{1/2} T_e^{-1}), \quad T_e > 10Z^2 \text{ eV} > T_i m_e/m_i;$$
$$= 30 - \ln(n_i^{1/2} T_i^{-3/2} Z^2 \mu^{-1}), \quad T_i > T_e m_i/m_e Z.$$

(c) Mixed ion-ion collisions

$$\lambda_{ii'} = \lambda_{i'i} = 23 - \ln\left[\frac{ZZ'(\mu + \mu')}{\mu T_{i'} + \mu' T_i}\left(\frac{n_i Z^2}{T_i} + \frac{n_{i'} Z'^2}{T_{i'}}\right)^{1/2}\right]$$

(d) Counterstreaming ions (relative velocity $v_D = \beta_D c$) in the presence of warm electrons, $kT_e/m_e > v_D^2 > kT_i/m_i, kT_{i'}/m_{i'}$.

$$\lambda_{ii'} = \lambda_{i'i} = 35 - \ln\left[\frac{ZZ'(\mu + \mu')}{\mu\mu'\beta_D^2}\left(\frac{n_e}{T_e}\right)^{1/2}\right].$$

Fokker-Planck Equation

$$\frac{Df^\alpha}{Dt} = \frac{\partial f^\alpha}{\partial t} + \mathbf{v}\cdot\nabla f^\alpha + \mathbf{F}\cdot\nabla_{\mathbf{v}} f^\alpha = \left(\frac{\partial f^\alpha}{\partial t}\right)_{coll},$$

where F is an external force field. The general form of the collision integral is $(\partial f^\alpha/\partial t)_{coll} = -\Sigma_\beta \nabla_{\mathbf{v}}\cdot \mathbf{J}^{\alpha/\beta}$ with

$$\mathbf{J}^{\alpha/\beta} = 2\pi\lambda_{\alpha\beta}\frac{e_\alpha^2 e_\beta^2}{m_\alpha}\int d^3v'(u^2\mathbf{I} - \mathbf{uu})u^{-3}\left\{\frac{1}{m_\beta}f^\alpha(\mathbf{v})\nabla_{\mathbf{v}'}f^\beta(\mathbf{v}') - \frac{1}{m_\alpha}f^\beta(\mathbf{v}')\nabla_{\mathbf{v}}f^\alpha(\mathbf{v})\right\}$$

(Landau form) where $\mathbf{u} = \mathbf{v}' - \mathbf{v}$ and $\mathbf{I}$ is the unit dyad, or alternatively

$$\mathbf{J}^{\alpha/\beta} = 4\pi\lambda_{\alpha\beta}\frac{e_\alpha^2 e_\beta^2}{m_\alpha^2}\left\{f^\alpha(\mathbf{v})\nabla_\mathbf{v} H(\mathbf{v}) - \frac{1}{2}\nabla_\mathbf{v}\cdot[f^\alpha(\mathbf{v})\nabla_\mathbf{v}\nabla_\mathbf{v} G(\mathbf{v})]\right\},$$

where the Rosenbluth potentials are

$$G(\mathbf{v}) = \int f^\beta(\mathbf{v}')u\,d^3v'$$

$$H(\mathbf{v}) = \left(1 + \frac{m_\alpha}{m_\beta}\right)\int f^\beta(\mathbf{v}')u^{-1}d^3v'.$$

If species α is a weak beam (number and energy density small compared with background) streaming through a Maxwellian plasma, then

$$\mathbf{J}^{\alpha/\beta} = -\nu_s^{\alpha/\beta}\mathbf{v}f^\alpha - \frac{1}{2}\nu_\perp^{\alpha/\beta}v^2\nabla_\mathbf{v} f^\alpha + \frac{1}{2}(\nu_\perp^{\alpha/\beta} - \nu_{\|}^{\alpha/\beta})\mathbf{v}\mathbf{v}\cdot\nabla_\mathbf{v} f^\alpha.$$

B-G-K Collision Operator

For distribution functions with no large gradients in velocity space, the Fokker-Planck collision terms can be approximated according to

$$\frac{Df_e}{Dt} = \nu_{ee}(F_e - f_e) + \nu_{ei}(\bar{F}_e - f_e);$$

$$\frac{Df_i}{Dt} = \nu_{ie}(\bar{F}_i - f_i) + \nu_{ii}(F_i - f_i).$$

The respective slowing-down rates $\nu_s^{\alpha/\beta}$ given in the Relaxation Rate section above can be used for $\nu_{\alpha\beta}$, assuming slow ions and fast electrons, with ϵ replaced by T_α. (For ν_{ee} and ν_{ii}, $\nu_\perp$ can equally well be used, and the result is insensitive to whether the slow- or fast-test-particle limit is employed.) The maxwellians F_j and $\bar{F}_j$ are given by

$$F_j = n_j\left[\frac{m_j}{2\pi kT_j}\right]^{3/2}\exp\left\{-\left[\frac{m_j(\mathbf{v} - \mathbf{u}_j)^2}{2kT_j}\right]\right\};$$

$$\bar{F}_j = n_j\left[\frac{m_j}{2\pi k\bar{T}_j}\right]^{3/2}\exp\left\{-\left[\frac{m_j(\mathbf{v} - \bar{\mathbf{u}}_j)^2}{2k\bar{T}_j}\right]\right\};$$

where n_j, $\mathbf{u}_j$ and T_j are the number density, mean drift velocity, and effective temperature obtained by taking moments of f_j. Some latitude in the definition of $\bar{T}_j$ and $\bar{u}_j$ is possible;[19] one choice is $\bar{T}_e = T_i$, $\bar{T}_i = T_e$, $\bar{\mathbf{u}}_e = \mathbf{u}_i$, $\bar{\mathbf{u}}_i = \mathbf{u}_e$.

Transport Coefficients

Transport equations for a multispecies plasma:

$$\frac{D^\alpha n_\alpha}{Dt} + n_\alpha \nabla \cdot \mathbf{v}_\alpha = 0;$$

$$m_\alpha n_\alpha \frac{D^\alpha \mathbf{v}_\alpha}{Dt} = -\nabla p_\alpha - \nabla \cdot \mathbf{P}_\alpha + Z_\alpha e n_\alpha \left[\mathbf{E} + \frac{1}{c}\mathbf{v}_\alpha \times \mathbf{B}\right] + \mathbf{R}_\alpha;$$

$$\frac{3}{2} n_\alpha k \frac{D^\alpha T_\alpha}{Dt} + p_\alpha \nabla \cdot \mathbf{v}_\alpha = -\nabla \cdot \mathbf{q}_\alpha - \mathbf{P}_\alpha : \nabla \mathbf{v}_\alpha + Q_\alpha.$$

Here $D^\alpha/Dt = \partial/\partial t + \mathbf{v}_\alpha \cdot \nabla$; $p_\alpha = n_\alpha k T_\alpha$, where k is Boltzmann's constant; $\mathbf{R}_\alpha = \Sigma_\beta \mathbf{R}_{\alpha\beta}$, and $Q_\alpha = \Sigma_\beta Q_{\alpha\beta}$, where $\mathbf{R}_{\alpha\beta}$ and $Q_{\alpha\beta}$ are respectively the momentum and energy gained by the α^{th} species through collisions with the β^{th}; $\mathbf{P}_\alpha$ is the stress tensor, and $\mathbf{q}_\alpha$ is the heat flow.

The transport coefficients in a simple two-component (electrons and singly charged ions) plasma are tabulated below. Here $||$ and $\perp$ refer to the direction of the magnetic field $\mathbf{B} = \mathbf{b}B$; $\mathbf{u} = \mathbf{v}_e - \mathbf{v}_i$ is the relative streaming velocity; $n_e = n_i = n$; $\mathbf{j} = -ne\mathbf{u}$ is the current; $\omega_{ce} = 1.76 \times 10^7\, B$ and $\omega_{ci} = (m_e/m_i)\omega_{ce}$ are the electron and ion gyrofrequencies, respectively; and the basic collisional times are taken to be

$$\tau_e = \frac{3\sqrt{m_e}(kT_e)^{3/2}}{4\sqrt{2\pi}\, n\lambda e^4} = 3.44 \times 10^5 \frac{T_e^{3/2}}{n\lambda},$$

where λ is the Coulomb logarithm, and

$$\tau_i = \frac{3\sqrt{m_i}(kT_i)^{3/2}}{4\sqrt{\pi}\, n\lambda e^4} = 2.09 \times 10^7 \frac{T_i^{3/2}}{n\lambda} \mu^{1/2}.$$

In the limit of large fields ($\omega_{cj}\tau_j >> 1$) the transport processes may be summarized as follows:[20]

momentum transfer	$\mathbf{R}_{ei} = -\mathbf{R}_{ie} = \mathbf{R} = \mathbf{R}_u + \mathbf{R}_T;$
frictional force	$\mathbf{R}_u = ne(\mathbf{j}_\perp/\sigma_\perp + \mathbf{j}_{\parallel}/\sigma_{\parallel});$
conductivities	$\sigma_{\parallel} = 2.0\,\sigma_\perp = 2.0\,\dfrac{ne^2\tau_e}{m_e};$
thermal force	$\mathbf{R}_T = -0.71\, nk\nabla_{\parallel}T_e - \dfrac{3}{2}\dfrac{nk}{\omega_{ce}\tau_e}\mathbf{b} \times \nabla_\perp T_e;$
ion heating	$Q_i = 3\dfrac{m_e}{m_i}\dfrac{nk}{\tau_e}(T_e - T_i);$

electron heating	$Q_e = -Q_i - \mathbf{R}\cdot\mathbf{u};$
ion heat flux	$\mathbf{q}_i = -\kappa_{\parallel}^i\nabla_{\parallel}kT_i - \kappa_{\perp}^i\nabla_{\perp}kT_i + \kappa_{\wedge}^i\mathbf{b}\times\nabla_{\perp}kT_i;$
ion thermal conductivities	$\kappa_{\parallel}^i = 3.9\dfrac{nkT_i\tau_i}{m_i};\quad \kappa_{\perp}^i = 2\dfrac{nkT_i}{m_i\omega_{ci}^2\tau_i};\quad \kappa_{\wedge}^i = \dfrac{5}{2}\dfrac{nkT_i}{m_i\omega_{ci}};$
electron heat flux	$\mathbf{q}^e = \mathbf{q}_u^e + \mathbf{q}_T^e;$
frictional heat flux	$\mathbf{q}_u^e = 0.71\,nkT_e\mathbf{u}_{\parallel} + \dfrac{3}{2}\dfrac{nkT_e}{\omega_{ce}\tau_e}\mathbf{b}\times\mathbf{u}_{\perp};$
thermal gradient heat flux	$\mathbf{q}_T^e = -\kappa_{\parallel}^e\nabla_{\parallel}kT_e - \kappa_{\perp}^e\nabla_{\perp}kT_e - \kappa_{\wedge}^e\mathbf{b}\times\nabla_{\perp}kT_e;$
electron thermal conductivities	$\kappa_{\parallel}^e = 3.2\dfrac{nkT_e\tau_e}{m_e};\quad \kappa_{\perp}^e = 4.7\dfrac{nkT_e}{m_e\omega_{ce}^2\tau_e};\quad \kappa_{\wedge}^e = \dfrac{5}{2}\dfrac{nkT_e}{m_e\omega_{ce}}$
stress tensor (both species)	$P_{xx} = -\dfrac{\eta_0}{2}(W_{xx}+W_{yy}) - \dfrac{\eta_1}{2}(W_{xx}-W_{yy}) - \eta_3W_{xy};$

$$P_{yy} = -\frac{\eta_0}{2}(W_{xx}+W_{yy}) + \frac{\eta_1}{2}(W_{xx}-W_{yy}) + \eta_3W_{xy};$$

$$P_{xy} = P_{yx} = -\eta_1W_{xy} + \frac{\eta_3}{2}(W_{xx}-W_{yy});$$

$$P_{xz} = P_{zx} = -\eta_2W_{xz} - \eta_4W_{yz};$$

$$P_{yz} = P_{zy} = -\eta_2W_{yz} + \eta_4W_{xz};$$

$$P_{zz} = -\eta_0W_{zz}$$

(here the z axis is defined parallel to $\mathbf{B}$);

ion viscosity	$\eta_0^i = 0.96\,nkT_i\tau_i;\quad \eta_1^i = \dfrac{3}{10}\dfrac{nkT_i}{\omega_{ci}^2\tau_i};\quad \eta_2^i = \dfrac{6}{5}\dfrac{nkT_i}{\omega_{ci}^2\tau_i};$
	$\eta_3^i = \dfrac{1}{2}\dfrac{nkT_i}{\omega_{ci}};\quad \eta_4^i = \dfrac{nkT_i}{\omega_{ci}};$
electron viscosity	$\eta_0^e = 0.73\,nkT_e\tau_e;\quad \eta_1^e = 0.51\dfrac{nkT_e}{\omega_{ce}^2\tau_e};\quad \eta_2^e = 2.0\dfrac{nkT_e}{\omega_{ce}^2\tau_e};$
	$\eta_3^e = -\dfrac{1}{2}\dfrac{nkT_e}{\omega_{ce}};\quad \eta_4^e = -\dfrac{nkT_e}{\omega_{ce}}.$

For both species the rate-of-strain tensor is defined as

$$W_{jk} = \frac{\partial v_j}{\partial x_k} + \frac{\partial v_k}{\partial x_j} - \frac{2}{3}\delta_{jk}\nabla \cdot \mathbf{v}.$$

When $\mathbf{B} = 0$ the following simplifications occur:

$$\mathbf{R}_u = ne\mathbf{j}/\sigma_{\parallel}; \quad \mathbf{R}_T = -\,0.71\,n\nabla kT_e; \quad \mathbf{q}_i = -\,\kappa_{\parallel}^i\nabla kT_i; \quad \mathbf{q}_u^e = 0.71\; nkT_e\mathbf{u};$$

$$\mathbf{q}_T^e = -\,\kappa_{\parallel}^e\nabla kT_e; \quad P_{jk} = -\eta_0 W_{jk}.$$

When $\omega_{ce}\tau_e >> 1 >> \omega_{ci}\tau_i$, the high-field expressions are obeyed by the electrons and the zero-field expressions by the ions.

Collisional transport theory is applicable when (1) macroscopic time rates of change satisfy $d/dt << 1/\tau$, where τ is the longest collisional time scale, and (in the absence of a magnetic field) (2) macroscopic length scales L satisfy $L >> \ell$, where $\ell = \bar{v}\tau$ is the mean free path. In a strong field, $\omega_{ce}\tau >> 1$, condition (2) is replaced by $L_{\parallel} >> \ell$ and $L_{\perp} >> \sqrt{\ell r_e}$ ($L_{\perp} >> r_e$ in a uniform field), where $L_{\parallel}$ is a macroscopic scale parallel to the field $\mathbf{B}$ and $L_{\perp}$ is the smaller of $(\nabla_{\perp}B/B)^{-1}$ and the transverse plasma dimension. In addition, the standard transport coefficients are valid only when (3) the Coulomb logarithm satisfies $\lambda >> 1$; (4) the electron gyroradius satisfies $r_e >> \lambda_D$, or $B^2 << 8\pi n_e m_e c^2$; (5) relative drifts $\mathbf{u} = \mathbf{v}_\alpha - \mathbf{v}_\beta$ between two species are small compared with the thermal velocities, $u << (kT_\alpha/m_\alpha)^{1/2}$, $(kT_\beta/m_\beta)^{1/2}$, and (6) anomalous transport processes owing to microinstabilities are negligible.

Weakly Ionized Plasmas

Collision frequency for scattering of charged particles by neutrals is

$$\nu_\alpha = n_0 \sigma_{0\alpha} (kT_\alpha / m_\alpha)^{1/2} \text{ sec}^{-1},$$

where n_0 is the neutral density and $\sigma_{0\alpha}$ is the cross-section, typically $\sim 5 \times 10^{-15}$ cm^2 and weakly dependent on temperature.

When the system size $L << \lambda_D$, the charged particle diffusion coefficients are

$$D_\alpha = kT_\alpha / m_\alpha \nu_\alpha \text{ cm}^2/\text{sec}.$$

In the opposite limit, both species diffuse at the ambipolar rate

$$D_A = \frac{\mu_i D_e - \mu_e D_i}{\mu_i - \mu_e} = \frac{(T_i + T_e) D_i D_e}{T_i D_e + T_e D_i} \text{ cm}^2/\text{sec},$$

where $\mu_\alpha = e_\alpha / m_\alpha \nu_\alpha$ is the mobility. The conductivity σ_α satisfies $\sigma_\alpha = n_\alpha e_\alpha \mu_\alpha$.

In the presence of a magnetic field $\mathbf{B}$, μ and σ become tensors

$$\mathbf{J}^\alpha = \boldsymbol{\sigma}^\alpha \cdot \mathbf{E} = \sigma^\alpha_{\parallel} \mathbf{E}_{\parallel} + \sigma^\alpha_{\perp} \mathbf{E}_{\perp} + \sigma^\alpha_{\wedge} \mathbf{E} \times \mathbf{b},$$

where $\mathbf{b} = \mathbf{B}/B$ and

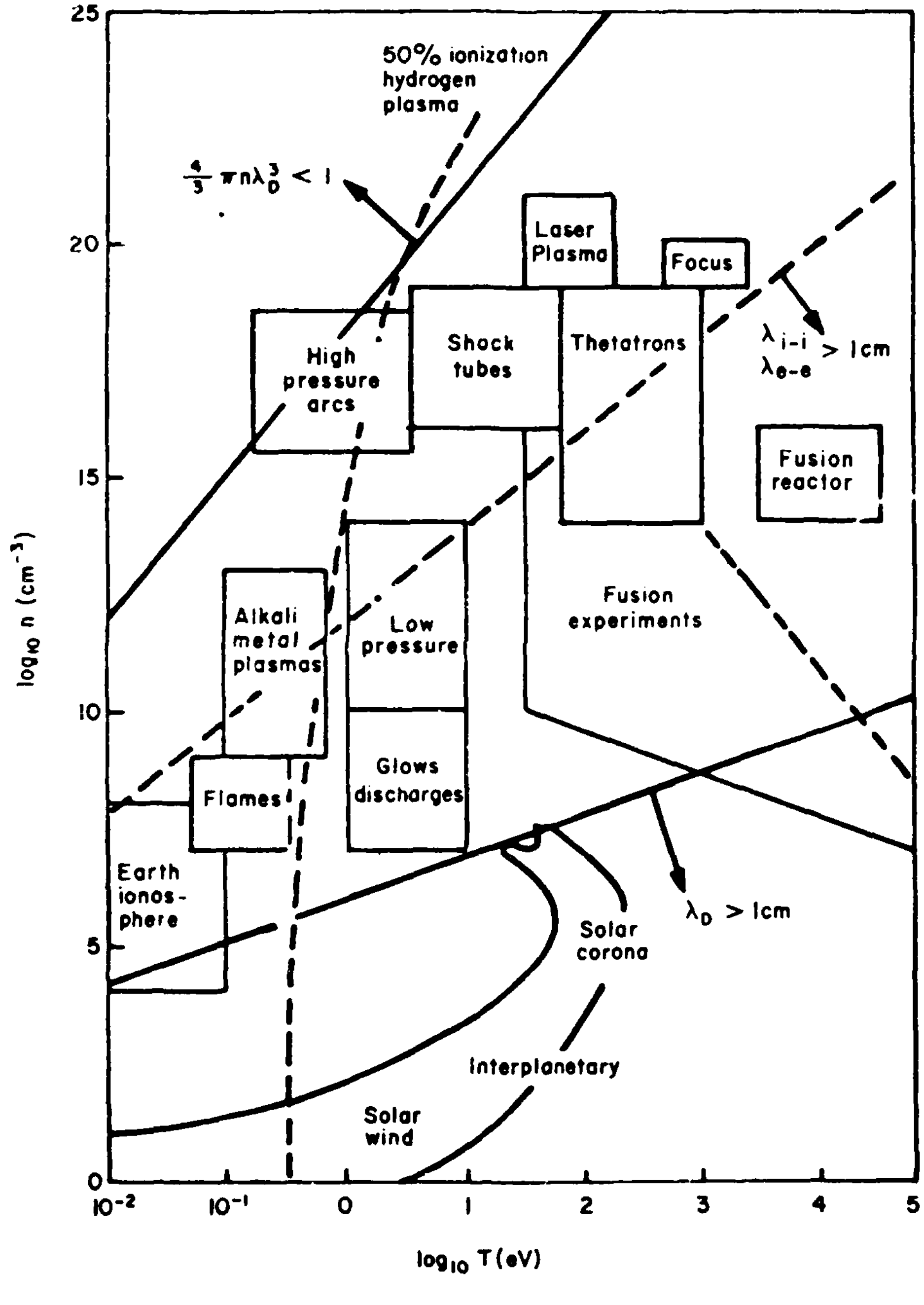
$$\sigma^\alpha_{\parallel} = n_\alpha e_\alpha^2 / m_\alpha \nu_\alpha; \; \sigma^\alpha_{\perp} = \sigma^\alpha_{\parallel} \nu_\alpha^2 / (\nu_\alpha^2 + \omega_{c\alpha}^2); \; \sigma^\alpha_{\wedge} = \sigma^\alpha_{\parallel} \nu_\alpha \omega_{c\alpha} / (\nu_\alpha^2 + \omega_{c\alpha}^2).$$

Here $\sigma_\perp$ and $\sigma_\wedge$ are the Pedersen and Hall conductivities, respectively.

APPROXIMATE MAGNITUDES IN SOME TYPICAL PLASMAS

Plasma Type	n cm^{-3}	T eV	ω_{pe} sec^{-1}	λ_D cm	$n\lambda_D^3$	ν_{ei} sec^{-1}
Interstellar gas	1	1	6×10^4	7×10^2	4×10^8	7×10^{-5}
Gaseous nebula	10^3	1	2×10^6	20	10^7	6×10^{-2}
Solar corona	10^6	10^2	6×10^7	7	4×10^8	6×10^{-2}
Diffuse hot plasma	10^{12}	10^2	6×10^{10}	7×10^{-3}	4×10^5	40
Solar atmosphere, gas discharge	10^{14}	1	6×10^{11}	7×10^{-5}	40	2×10^9
Warm plasma	10^{14}	10	6×10^{11}	2×10^{-4}	10^3	10^7
Hot plasma	10^{14}	10^2	6×10^{11}	7×10^{-4}	4×10^4	4×10^6
Thermonuclear plasma	10^{15}	10^4	2×10^{12}	2×10^{-3}	10^7	5×10^4
Theta pinch	10^{16}	10^2	6×10^{12}	7×10^{-5}	4×10^3	3×10^8
Dense hot plasma	10^{18}	10^2	6×10^{13}	7×10^{-6}	4×10^2	2×10^{10}
Laser plasma	10^{20}	10^2	6×10^{14}	7×10^{-7}	40	2×10^{12}

The diagram (facing) gives comparable information in graphical form.[21]



50% ionization
hydrogen
plasma
$\frac{4}{3}\pi n\lambda_D^3 < 1$
Laser
Plasma
Focus
High
pressure
arcs
Shock
tubes
Thetatrons
λ_{i-i}
λ_{e-e} > 1cm
Fusion
reactor
Alkali
metal
plasmas
Low
pressure
Fusion
experiments
Glows
discharges
Flames
Earth
ionos-
phere
λ_D > 1cm
Solar
corona
Interplanetary
Solar
wind
$\log_{10} n\ (cm^{-3})$
$\log_{10} T(eV)$

IONOSPHERIC PARAMETERS[22]

The following tables gives average nighttime values. Where two numbers are entered, the first refers to the lower and the second to the upper portion of the layer.

Quantity	E Region	F Region
Altitude (km)	90–160	160–500
Number density (m^{-3})	$1.5 \times 10^{10} - 3.0 \times 10^{10}$	$5 \times 10^{10} - 2 \times 10^{11}$
Height-integrated number density (m^{-2})	9×10^{14}	4.5×10^{15}
Ion-neutral collision frequency (sec^{-1})	$2 \times 10^{3} - 10^{2}$	$0.5 - 0.05$
Ion gyro-/collision frequency ratio κ_i	$0.09 - 2.0$	$4.6 \times 10^{2} - 5.0 \times 10^{3}$
Ion Pedersen factor $\kappa_i/(1 + \kappa_i^2)$	$0.09 - 0.5$	$2.2 \times 10^{-3} - 2 \times 10^{-4}$
Ion Hall factor $\kappa_i^2/(1 + \kappa_i^2)$	$8 \times 10^{-4} - 0.8$	1.0
Electron-neutral collision frequency	$1.5 \times 10^{4} - 9.0 \times 10^{2}$	80 - 10
Electron gyro-/collision frequency ratio κ_e	$4.1 \times 10^{2} - 6.9 \times 10^{3}$	$7.8 \times 10^{4} - 6.2 \times 10^{5}$
Electron Pedersen factor $\kappa_e/(1 + \kappa_e^2)$	$2.7 \times 10^{-3} - 1.5 \times 10^{-4}$	$10^{-5} - 1.5 \times 10^{-6}$
Electron Hall factor $\kappa_e^2/(1 + \kappa_e^2)$	1.0	1.0
Mean molecular weight	28 - 26	22 - 16
Ion gyrofrequency (sec^{-1})	180 - 190	230 - 300
Neutral diffusion coefficient (m^2/sec)	$30 - 5 \times 10^{3}$	10^{5}

The terrestrial magnetic field in the lower ionosphere at equatorial latitudes is approximately $B_0 = 0.35 \times 10^{-4}$ tesla. The earth's radius is $R_E = 6371$ km.

SOLAR PHYSICS PARAMETERS[23]

Parameter	Symbol	Value	Units
Total mass	$M_\odot$	1.99×10^{33}	g
Radius	$R_\odot$	6.96×10^{10}	cm
Surface gravity	$g_\odot$	2.74×10^4	cm s^{-2}
Escape speed	v_∞	6.18×10^7	cm s^{-1}
Upward mass flux in spicules	—	1.6×10^{-9}	g cm^{-2} s^{-1}
Vertically integrated atmospheric density	—	4.28	g cm^{-2}
Sunspot magnetic field strength	B_{max}	2500-3500	G
Surface temperature	T_0	6420	K
Radiant power	$\mathcal{L}_\odot$	3.90×10^{33}	erg s^{-1}
Radiant flux density	$\mathcal{F}$	6.41×10^{10}	erg cm^{-2} s^{-1}
Optical depth at 500 nm, measured from photosphere	τ_{500}	0.99	—
Astronomical unit (radius of earth's orbit)	AU	1.50×10^{13}	cm
Solar constant (radiant flux density at 1 AU)	f	1.39×10^6	erg cm^{-2}

Chromosphere and Corona[24]

Parameter (Units)	Quiet Sun	Coronal Hole	Active Region
Chromospheric radiation losses (erg cm^{-2} s^{-1})			
Low chromosphere	2×10^6	2×10^6	$\gtrsim 10^7$
Middle chromosphere	2×10^6	2×10^6	10^7
Upper chromosphere	3×10^5	3×10^5	2×10^6
Total	4×10^6	4×10^6	$\gtrsim 2 \times 10^7$
Transition layer pressure (dyne cm^{-2})	0.2	0.07	2
Coronal temperature (K, at 1.1 $R_\odot$)	$1.1\text{-}1.6 \times 10^6$	10^6	2.5×10^6
Coronal energy losses (erg cm^{-2} s^{-1})			
Conduction	2×10^5	6×10^4	$10^5\text{-}10^7$
Radiation	10^5	10^4	5×10^6
Solar wind	$\lesssim 5 \times 10^4$	7×10^5	$< 10^5$
Total	3×10^5	8×10^5	10^7
Solar wind mass loss (g cm^{-2} s^{-1})	$\lesssim 2 \times 10^{-11}$	2×10^{-10}	$< 4 \times 10^{-11}$

THERMONUCLEAR FUSION[25]

Natural abundance of deuterium $n_D/n_H = 1.5 \times 10^{-4}$

Mass ratios	$m_e/m_D = 2.72 \times 10^{-4} = 1/3670$
	$(m_e/m_D)^{1/2} = 1.65 \times 10^{-2} = 1/60.6$
	$m_e/m_T = 1.82 \times 10^{-4} = 1/5496$
	$(m_e/m_T)^{1/2} = 1.35 \times 10^{-2} = 1/74.1$

Fusion reactions (branching ratios are correct for energies near the cross-section peaks; a negative yield means the reaction is endothermic):[26]

$$\text{(1a)}\quad D + D \xrightarrow[50\%]{} T(1.01\ \text{MeV}) + p(3.02\ \text{MeV})$$

$$\text{(1b)}\quad \xrightarrow[50\%]{} He^3(0.82\ \text{MeV}) + n(2.45\ \text{MeV})$$

$$\text{(2)}\quad D + T \longrightarrow He^4(3.5\ \text{MeV}) + n(14.1\ \text{MeV})$$

$$\text{(3)}\quad D + He^3 \longrightarrow He^4(3.6\ \text{MeV}) + p(14.7\ \text{MeV})$$

$$\text{(4)}\quad T + T \longrightarrow He^4 + 2n + 11.3\ \text{MeV}$$

$$\text{(5a)}\quad He^3 + T \xrightarrow[51\%]{} He^4 + p + n + 12.1\ \text{MeV}$$

$$\text{(5b)}\quad \xrightarrow[43\%]{} He^4(4.8\ \text{MeV}) + D(9.5\ \text{MeV})$$

$$\text{(5c)}\quad \xrightarrow[6\%]{} He^5(2.4\ \text{MeV}) + p(11.9\ \text{MeV})$$

$$\text{(6)}\quad p + Li^6 \longrightarrow He^4(1.7\ \text{MeV}) + He^3(2.3\ \text{MeV})$$

$$\text{(7a)}\quad p + Li^7 \xrightarrow[\sim 20\%]{} 2\,He^4 + 17.3\ \text{MeV}$$

$$\text{(7b)}\quad \xrightarrow[\sim 80\%]{} Be^7 + n - 1.6\ \text{MeV}$$

$$\text{(8)}\quad D + Li^6 \longrightarrow 2\,He^4 + 22.4\ \text{MeV}$$

$$\text{(9)}\quad p + B^{11} \longrightarrow 3\,He^4 + 8.7\ \text{MeV}$$

$$\text{(10)}\quad n + Li^6 \longrightarrow He^4(2.1\ \text{MeV}) + T(2.7\ \text{MeV})$$

The total cross section in barns as a function of E, the energy in keV of the incident particle [the first ion on the left side of Eqs. (1)-(5)], assuming the target ion at rest, can be fitted by[27]

$$\sigma_T(E) = \frac{A_5 + [(A_4 - A_3E)^2 + 1]^{-1}A_2}{E[\exp(A_1/\sqrt{E}) - 1]}$$

where the Duane coefficients A_j for the principal fusion reactions are as follows:

	D – D (1a)	D – D (1b)	D – T (2)	D – He³ (3)	T – T (4)	T – He³ (5)
A_1	46.097	47.88	45.95	89.27	38.39	123.1
A_2	372	482	5.02×10^4	2.59×10^4	448	1.125×10^4
A_3	4.36×10^{-4}	3.08×10^{-4}	1.368×10^{-2}	3.98×10^{-3}	1.02×10^{-3}	0
A_4	1.220	1.177	1.076	1.297	2.09	0
A_5	0	0	409	647	0	0

Reaction rates σv (cm³/sec), averaged over Maxwellian distributions:

Temperature (keV)	D – D (1a+1b)	D – T (2)	D – He³ (3)	T – T (4)	T – He³ (5a+5b+5c)
1.0	1.5×10^{-22}	5.5×10^{-21}	3×10^{-26}	3.3×10^{-22}	10^{-28}
2.0	5.4×10^{-21}	2.6×10^{-19}	1.4×10^{-23}	7.1×10^{-21}	10^{-25}
5.0	1.8×10^{-19}	1.3×10^{-17}	6.7×10^{-21}	1.4×10^{-19}	2.1×10^{-22}
10.0	1.2×10^{-18}	1.1×10^{-16}	2.3×10^{-19}	7.2×10^{-19}	1.2×10^{-20}
20.0	5.2×10^{-18}	4.2×10^{-16}	3.8×10^{-18}	2.5×10^{-18}	2.6×10^{-19}
50.0	2.1×10^{-17}	8.7×10^{-16}	5.4×10^{-17}	8.7×10^{-18}	5.3×10^{-18}
100.0	4.5×10^{-17}	8.5×10^{-16}	1.6×10^{-16}	1.9×10^{-17}	2.7×10^{-17}
200.0	8.8×10^{-17}	6.3×10^{-16}	2.4×10^{-16}	4.2×10^{-17}	9.2×10^{-17}
500.0	1.8×10^{-16}	3.7×10^{-16}	2.3×10^{-16}	8.4×10^{-17}	2.9×10^{-16}
1000.0	2.2×10^{-16}	2.7×10^{-16}	1.8×10^{-16}	8.0×10^{-17}	5.2×10^{-16}

For low energies ($T \leq 25$ keV) the data may be represented by

$$(\overline{\sigma v})_{DD} = 2.33 \times 10^{-14}\, T^{-2/3} \exp(-18.76\, T^{-1/3}) \text{ cm}^3/\text{sec};$$

$$(\overline{\sigma v})_{DT} = 3.68 \times 10^{-12}\, T^{-2/3} \exp(-19.94\, T^{-1/3}) \text{ cm}^3/\text{sec},$$

where T is measured in keV.

The power density released in the form of charged particles is

$$P_{DD} = 3.3 \times 10^{-13}\, n_D^2 (\overline{\sigma v})_{DD} \text{ watt/cm}^3 \text{ (including subsequent D-T reaction)}$$

$$P_{DT} = 5.6 \times 10^{-13}\, n_D n_T (\overline{\sigma v})_{DT} \text{ watt/cm}^3$$

$$P_{DHe^3} = 2.9 \times 10^{-12}\, n_D n_{He^3} (\overline{\sigma v})_{DHe^3} \text{ watt/cm}^3$$

The curie (abbreviated Ci) is a measure of radioactivity: 1 curie = 3.7×10^{10} counts/sec. Absorbed radiation dose is measured in rads: 1 rad = 10^2 erg/g.

RELATIVISTIC ELECTRON BEAMS

Here $\gamma = (1 - \beta^2)^{-1/2}$ is the relativistic scaling factor; in analytic formulas units are mks or cgs, as indicated; in numerical formulas, I is in amps, B in gauss, electron density N in cm^{-1}, and temperature, voltage and energy in MeV; $\beta_z = v_z/c$; k is Boltzmann's constant.

Relativistic electron gyroradius:

$$r_e = \frac{mc^2}{eB} (\gamma^2 - 1)^{1/2} \text{ (cgs)} = 1.70 \times 10^3 (\gamma^2 - 1)^{1/2} B \text{ cm.}$$

Relativistic electron energy:

$$W = mc^2\gamma \text{ (cgs)} = 0.511\, \gamma \text{ MeV.}$$

Bennett pinch condition:

$$I^2 = 2Nk(T_e + T_i)c^2 \text{ (cgs)} = 3.20 \times 10^{-4}\, N(T_e + T_i) \text{ A}^2.$$

Alfvén-Lawson limit:

$$I_A = (mc^3/e)\, \beta_z\gamma \text{ (cgs)} = (4\pi\, mc/\mu_0 e)\, \beta_z\gamma \text{ (mks)} = 1.70 \times 10^4\, \beta_z\gamma \text{ A.}$$

The ratio of net current to I_A is

$$I/I_A = \nu/\gamma,$$

where $\nu = Nr_e$, with $r_e = e^2/mc^2 = 2.82 \times 10^{-13}$ cm. Beam electron number density is

$$n_b = 2.08 \times 10^8\, J/\beta \text{ cm}^{-3},$$

where J is current density in A/cm^2. For a uniform beam of radius a (in cm),

$$n_b = 6.63 \times 10^7\, I/\beta a^2 \text{ cm}^{-3},$$

and

$$2r_e/a = \nu/\gamma.$$

Child's law: (non-relativistic) space-charge limited current density between parallel plates with voltage drop V and separation d in cm

$$J = 2.34 \times 10^3 V^{3/2} d^{-2} \quad \text{A cm}^{-2}.$$

The saturated parapotential current (magnetically self-limited flow along equipotentials in pinched diodes and transmission lines) is[28]

$$I_p = 8.5 \times 10^3 G\gamma \ln [\gamma + (\gamma^2 - 1)^{1/2}] \text{ A},$$

where G is a geometrical factor depending on the diode structure:

$G = \dfrac{w}{2\pi d}$ for parallel plane cathode and anode of width w, separation d;

$G = \left(\ln \dfrac{R_2}{R_1}\right)^{-1}$ for cylinders of radii R_1 (inner) and R_2 (outer);

$G = \dfrac{R_c}{d_0}$ for conical cathode of radius R_c, maximum separation d_0 (at $r = R_c$) from plane anode.

For $\beta \to 0$ ($\gamma \to 1$), both I_A and I_p vanish.

The condition for suppression of filamentation in a beam of current density J A cm^{-2} by a longitudinal magnetic field B_z is

$$B_z > 47\, \beta_z (\gamma J)^{1/2} \text{ G}.$$

Voltage registered by Rogowski coil of minor cross-sectional area A, n turns, major radius a, inductance L, external resistance R and capacitance C (all in mks):

externally integrated $\quad V = (1/RC)(nA\mu_0 I/2\pi a)$;

self-integrating $\quad V = (R/L)(nA\mu_0 I/2\pi a) = RI/n.$

X-ray production for target with average atomic number Z ($V \lesssim 5$ MeV)

$$\eta = \text{x-ray power/beam power} = 7 \times 10^{-4}\, ZV.$$

X-ray dose at 1 meter generated by an e-beam depositing total charge Q coulombs while $V \geq .84\, V_{max}$ in material with charge state Z

$$D = 150\, V_{max}^{2.8}\, QZ^{1/2} \text{ rads}.$$

BEAM INSTABILITIES[29]

Name	Conditions	Parameters of Most Unstable Mode				Saturation Mechanism
		Growth Rate	Frequency	Wave Number	Group Velocity	
Electron-electron	$V_d > V_{ej},\ j = 1, 2$	$\frac{1}{2}\omega_e$	0	$\frac{\sqrt{3}}{2}\omega_e/V_d$	0	Electron trapping until $\bar{V}_e \sim V_d$
Beam-plasma	$(n_b/n_p)^{1/3} > \bar{V}_b/V_b$	$\frac{\sqrt{3}}{2^{4/3}}\left(\frac{n_b}{n_p}\right)^{1/3}\omega_e$	$\omega_e\left[1 - \frac{1}{2^{4/3}}(n_b/n_p)^{1/3}\right]$	ω_e/V_d	$\frac{2}{3}V_b$	Trapping of beam electrons
Buneman	$V_d > (M/m)^{1/3}\bar{V}_i$, $V_d > \bar{V}_e$	$\frac{\sqrt{3}}{2^{4/3}}\left(\frac{m}{M}\right)^{1/3}\omega_e$	$\frac{1}{2^{4/3}}\omega_e(m/M)^{1/3}$	ω_e/V_d	$\frac{2}{3}V_d$	Electron trapping until $\bar{V}_e \sim V_d$
Weak beam-plasma	$\bar{V}_b/V_b > (n_b/n_p)^{1/3}$	$\frac{1}{2}\frac{n_b}{n_p}\left(\frac{V_b}{\bar{V}_b}\right)^2\omega_e$	ω_e	ω_e/V_b	$3\bar{V}_e^2/V_b$	Quasilinear or non-linear (mode coupling)
Beam-plasma (hot electron)	$\bar{V}_e > V_b > \bar{V}_b$, $(n_b/n_p)^{1/2}\bar{V}_e > \bar{V}_b$	$\left(\frac{n_b}{n_p}\right)^{1/2}\frac{\bar{V}_e}{V_b}\omega_e$	$\frac{V_b}{\bar{V}_e}\omega_e$	λ_D^{-1}	V_b	Quasilinear or non-linear
Ion acoustic	$T_e >> T_i$, $V_d > C_s$	$\left(\frac{m}{M}\right)^{1/2}\omega_i$	$\frac{C_s}{\bar{V}_e}\omega_e$	λ_D^{-1}	C_s	Quasilinear; ion tail formation; non-linear scattering; or resonance broadening.

Name	Condition	Parameters of Most Unstable Mode: Growth Rate	Frequency	Wave Number	Group Velocity	Saturation Mechanism
Anisotropic temperature (*hydro*)	$\frac{T_{\parallel}^{e}}{T_{\perp}^{e}} < \frac{1}{2}$	Ω_e	$\omega_e \cos\theta \sim \Omega_e$	r_e^{-1}	$\bar{V}_{e\perp}$	Isotropization
Ion Cyclotron	$V_d > 20\,\bar{V}_i$ (for $T_e \approx T_i$)	$0.1\,\Omega_i$	$1.2\,\Omega_i$	r_i^{-1}	$\frac{1}{3}\bar{V}_i$	Ion heating
Beam cyclotron (hydro)	$V_d > C_s$	$\frac{1}{\sqrt{2}}\Omega_e$	$n\Omega_e$	$\frac{1}{\sqrt{2}}\lambda_D^{-1}$	$V_d \leq V_R \leq C_s$	Resonance broadening
Modified two stream (hydro)	$\sqrt{1+\beta}\,V_A > V_d > C_s$	$\frac{1}{2}\Omega_H$	$\frac{\sqrt{3}}{2}\Omega_H$	$\sqrt{3}\,\frac{\Omega_H}{V_d}$	$\frac{1}{2}V_d$	Trapping
Ion-Ion (equal beam)	$U < 2V_A\sqrt{1+\beta}$	$\frac{1}{2\sqrt{2}}\Omega_H$	0	$\sqrt{3/2}\,\frac{\Omega_H}{U}$	0	Ion trapping
Ion-Ion (equal beam)	$U < 2\,C_s$	$\frac{1}{2\sqrt{2}}\omega_i$	0	$\sqrt{3/2}\,\frac{\omega_i}{U}$	0	Ion trapping

For nomenclature, see p. 50.

In the preceding table, subscripts e, i, d, b stand for "electron," "ion," "drift," and "beam," respectively. Thermal velocities are denoted by a bar. In addition, the following are used:

m	electron mass	λ_D	Debye length
M	ion mass	r_e, r_i	gyroradius
V	velocity	β	plasma/magnetic energy density ratio
T	temperature	V_A	Alfven speed
n_e, n_i	number density	Ω_e, Ω_i	gyro frequency
n	harmonic number	Ω_H	hybrid gyro frequency, $\Omega_H^2 = \Omega_e\Omega_i$
$C_s = (T_e/M)^{1/2}$	ion sound speed	U	relative drift velocity of two ion species
ω_e, ω_i	plasma frequency		

LASERS

System Parameters

Efficiencies and power levels are approximately state-of-the-art (1980).[30]

Type	Wavelength (microns)	Efficiency	Power levels available (W)	
			Pulsed	CW
CO_2	10.6	0.01–0.02 pulsed	$> 2 \times 10^{13}$	$> 10^5$
CO	5	0.4	$> 10^9$	> 100
Iodine	1.315	0.003	$> 10^{12}$	–
Nd-glass, YAG	1.06	0.001	$> 2 \times 10^{13}$ (20-beam system)	$1-10^3$
Ruby	0.6943	$< 10^{-3}$	10^{10}	1
He-Ne	0.6328	10^{-4}	–	$1\text{-}50 \times 10^{-3}$
Argon ion	0.45–0.60	10^{-3}	5×10^4	1–10
N_2	0.3371	$10^{-3}-0.05$	10^5-10^6	–
Kr-F	0.26	0.08	3×10^8	–
Xenon	0.175	0.02	$> 10^8$	–

Formulas

An e-m wave with **k** ∥ **B** has an index of refraction given by

$$n_\pm = [1 - \omega_{pe}^2/\omega(\omega \mp \omega_{ce})]^{1/2}$$

where ± refers to the helicity. The rate of change of polarization angle θ as a function of displacement s (Faraday rotation) is given by

$$d\theta/ds = (k/2)(n_- - n_+) = 2.36 \times 10^4 \; NBf^{-2} \text{ cm}^{-1},$$

where N is the electron number density, B is the field strength, and f is the wave frequency, all in cgs.

The quiver velocity of an electron in an e-m field of angular frequency ω is

$$v_0 = eE_{max}/m\omega = 25.6\sqrt{I}\,\lambda_0 \text{ cm/sec}$$

in terms of the laser flux $I = cE_{max}^2/8\pi$, with I in watts/cm², laser wavelength λ_0 in microns.

The ratio of quiver energy to thermal energy is

$$W_{qu}/W_{th} = m_e v_0^2/2kT = 1.81 \times 10^{-13} \lambda_0^2 I/T,$$

T in eV. E.g., if $I = 10^{15}$ watts/cm², $\lambda_0 = 1\ \mu$m, $T = 2$ keV, $W_{qu}/W_{th} \approx 0.1$.

Ponderomotive force

$$f = N \nabla \langle E^2 \rangle / 8\pi N_c$$

where

$$N_c = 1.1 \times 10^{21} \lambda_0^{-2} \text{ cm}^{-3}.$$

For uniform illumination of a lens with f-number F, the diameter d at focus (85% of the energy) and the depth of focus l (distance to first zero in intensity) are given by

$$d \approx 2.44\, F\lambda\, \theta/\theta_{DL} \quad \text{and} \quad l \approx \pm 2\, F^2\lambda\, \theta/\theta_{DL}.$$

Here θ is the beam divergence containing 85% of energy and θ_{DL} is the diffraction limited divergence:

$$\theta_{DL} = 2.44\, \lambda/b,$$

where b is the aperture. These formulas are modified for nonuniform (such as gaussian) illumination of the lens or for pathological laser profiles.

ATOMIC PHYSICS AND RADIATION

Energies and temperatures are in eV; all other units are cgs except where noted. Z is the charge state ($Z=0$ refers to a neutral atom); the subscript e labels electrons. N refers to number density, n to principal quantum number. Asterisk superscripts on level population densities denote local thermodynamic equilibrium (LTE) values. Thus $N_n{}^*$ is the LTE number density of atoms (or ions) in level n.

Characteristic atomic collision cross section

(1) $$\pi a_0^2 = 8.80 \times 10^{-17}\ \mathrm{cm}^2.$$

Binding energy for outer electron in level labelled by quantum numbers n, l

(2) $$E_\infty{}^Z(n,l) = -\frac{Z^2 E_\infty{}^H}{(n-\Delta_l)^2},$$

where $E_\infty{}^H = 13.6$ eV is the hydrogen ionization energy and $\Delta_l = 0.75 l^{-5}$, $l \gtrsim 5$, is the quantum defect.

Excitation and Decay

Cross section (Bethe approximation) for electron excitation by dipole allowed transition $m \rightarrow n$[31,32]

(3) $$\sigma_{mn} = 2.36 \times 10^{-13} \frac{f_{nm} g(n,m)}{\epsilon \Delta E_{nm}}\ \mathrm{cm}^2,$$

where f_{nm} is the oscillator strength, $g(n,m)$ is the Gaunt factor, ϵ is the incident electron energy, and $\Delta E_{nm} = E_n - E_m$.

Electron excitation rate averaged over Maxwellian velocity distribution[33,34]

(4) $$X_{mn} = N_e < \sigma_{mn} v > = \frac{1.6 \times 10^{-5} f_{nm} \langle g(n,m) \rangle N_e}{\Delta E_{nm} \sqrt{T_e}} \exp\left(-\frac{\Delta E_{nm}}{T_e}\right)\ \mathrm{sec}^{-1},$$

where $\langle g(n,m) \rangle$ denotes the thermal averaged Gaunt factor (generally ~ 1 for atoms, ~ 0.2 for ions).

Rate for electron collisional deexcitation

(5) $$Y_{nm} = (N_m{}^*/N_n{}^*) X_{mn}\ \mathrm{sec}^{-1}.$$

Here $N_m{}^*/N_n{}^* = (g_m/g_n) \exp(\Delta E_{nm}/T_e)$ is the Boltzmann relation for level population densities, where g_n is the statistical weight of level n.

Rate for spontaneous decay $n \rightarrow m$ (Einstein A coefficient)[33]

(6) $$A_{nm} = 4.3 \times 10^{7} \frac{g_n}{g_m} f_{nm}(\Delta E_{nm})^2 \text{ sec}^{-1},$$

Intensity emitted per unit volume from the transition $n \rightarrow m$ in an optically thin plasma

(7) $$I_{nm} = 1.6 \times 10^{-19} A_{nm} N_n \Delta E_{nm} \text{ watts/cm}^3.$$

Condition for steady state in a corona model

(8) $$N_0 N_e \langle \sigma_{0n} v \rangle = N_n A_{n0},$$

where the ground state is labelled by a subscript zero.

Hence for a transition $n \rightarrow m$ in ions, where $\langle g(n,0) \rangle \approx 0.2$,

(9) $$I_{nm} = 5.1 \times 10^{-25} f_{nm} (g_0/g_m)(\Delta E_{nm}/\Delta E_{no})^3 N_e N_o T_e^{-1/2} \exp(-\Delta E_{no}/T_e) \text{ watts/cm}^3.$$

Ionization and Recombination

In a general time-dependent situation the number density of the charge state Z satisfies

(10) $$\frac{dN(Z)}{dt} = N_e[-S(Z)N(Z) - \alpha(Z)N(Z) + S(Z-1)N(Z-1) + \alpha(Z+1)N(Z+1)].$$

Here $S(Z)$ is the ionization rate. The recombination rate $\alpha(Z)$ has the form $\alpha(Z) = \alpha_r(Z) + N_e\alpha_3(Z)$, where α_r and α_3 are the radiative and three-body recombination rates, respectively.

Classical ionization cross-section[35] for any atomic shell k

(11) $$\sigma_i = 6 \times 10^{-14} \; b_k g_k(x)/U_k^2 \text{ cm}^2;$$

Here b_k is the number of shell electrons, U_k is the binding energy of the ejected electron, $x = \epsilon/U_k$, where ϵ is the incident electron energy, and g is a universal function with a maximum value ≈ 0.2 at $x \approx 4$.

Ionization from ion ground state, averaged over Maxwellian electron distribution for $0.02 \leq T_e/E_\infty{}^Z \leq 100$ (Ref. 34):

(12) $$S(Z) = \frac{10^{-5}(T_e/E_\infty{}^Z)^{1/2}}{(E_\infty{}^Z)^{3/2}(6 + T_e/E_\infty{}^Z)} \exp(-E_\infty{}^Z/T_e) \text{ cm}^3/\text{sec},$$

where $E_\infty{}^Z$ is the ionization energy.

Electron-ion radiative recombination rate $[e + N(Z) \rightarrow N(Z-1) + h\nu]$ for $T_e/Z^2 \leq 400$ eV (Ref. 36):

(13) $$\alpha_r(Z) = 5.2 \times 10^{-14} Z \sqrt{E_\infty{}^Z/T_e}\,\{0.43 + (1/2) \ln (E_\infty^Z/T_e) + 0.469\,(E_\infty{}^Z/T_e)^{-1/3}\} \text{ cm}^3/\text{sec}.$$

For 1 eV $< T_e/Z^2 <$ 15 eV, this becomes approximately[34]

(14) $$\alpha_r(Z) = 2.7 \times 10^{-13}\, Z^2 T_e^{-1/2} \text{ cm}^3/\text{sec}.$$

Collisional (three-body) recombination rate for singly ionized plasma[37]

(15) $$\alpha_3 = 8.75 \times 10^{-27} T_e^{-4.5} \text{ cm}^6/\text{sec}.$$

Photoionization cross section for ions in level n, l (short wavelength limit)

(16) $$\sigma_{ph}(n,l) = 1.64 \times 10^{-16} Z^5/(n^3 K^{7+2l}),$$

where K is wavenumber in Rydberg units (1 Rydberg $= 1.0974 \times 10^5$ cm^{-1}).

Ionization Equilibrium Models

Saha equilibrium[38]

$$N_e N_1^*(Z) / N_n^*(Z-1) = 6.0 \times 10^{21} \frac{g_1^Z T_e^{3/2}}{g_n^{Z-1}} \exp\left(-\frac{E_\infty^Z(n,l)}{T_e}\right) \text{ cm}^{-3}, \tag{17}$$

where g_n^Z is the statistical weight for level n of charge state Z and $E_\infty^Z(n,l)$ is the ionization energy of the neutral atom initially in level (n,l).

In a steady state at high electron density

$$N_e N^*(Z)/N^*(Z-1) = S(Z-1)/\alpha_3 \text{ cm}^{-3}, \tag{18}$$

a function only of T.

Conditions for LTE[38]

(a) Collisional and radiative excitation rates for a level n must satisfy

$$Y_{nm}/A_{nm} > 10. \tag{19}$$

(b) Electron density must satisfy

$$N_e \geq 7 \times 10^{18} Z^7 n^{-17/2} (T/E_\infty^Z)^{1/2} \text{ cm}^{-3}. \tag{20}$$

Steady state condition in corona model

$$\frac{N(Z\text{-}1)}{N(Z)} = \frac{\alpha_r}{S(Z\text{-}1)}. \tag{21}$$

Corona model is applicable if[39]

$$10^{12} t_I^{-1} < N_e < 10^{16} T_e^{7/2} \text{ cm}^{-3}, \tag{22}$$

where t_I^{-1} is the inverse ionization time.

Radiation

N.B. Energies and temperatures are in eV; all other units are cgs except where noted. Z is the charge state ($Z = 0$ refers to a neutral atom); the subscript e labels electrons. N refers to number density.

Average radiative decay rate of state with principal quantum number n is

(23) $$A_n = \sum_{m<n} A_{nm} = 1.6 \times 10^{10}\, Z^4\, n^{-9/2} \text{ sec.}$$

Natural line width (ΔE in eV)

(24) $$\Delta E\, \Delta t = h = 4.14 \times 10^{-15} \text{ eV-sec}$$

where Δt is the lifetime of the line.

Doppler width

(25) $$\Delta\lambda/\lambda = 7.7 \times 10^{-5}\ (T/\mu)^{1/2},$$

where μ is the emitting atom or ion mass in units of the proton mass.

Optical depth for a Doppler broadened line[38]

(26) $$\tau = 1.76 \times 10^{-13}\, \lambda (Mc^2/kT)^{1/2} Nl = 5.4 \times 10^{-9}\, \lambda (\mu/T)^{1/2} Nl,$$

where λ is wavelength and l the physical depth of the plasma; M, N and T are mass, number density and temperature of the absorber; μ is M divided by the proton mass. Optically thin means $\tau < 1$.

Resonance absorption cross section at center of line

(27) $$\sigma_{\lambda=\lambda_c} = 5.6 \times 10^{-13}\ \lambda^2/\Delta\lambda \text{ cm}^2.$$

Wien displacement law: wavelength of maximum black body emission is given by

(28) $$\lambda_{max} = 2.50 \times 10^{-5}\ T^{-1} \text{ cm.}$$

Radiation from surface of black body of temperature T

(29) $$W = 1.03 \times 10^5\ T^4 \text{ watts/cm}^2.$$

Bremsstrahlung from hydrogen-like plasma[25]

(30) $$P_{Br} = 1.69 \times 10^{-32} N_e T_e^{1/2} \Sigma \, [Z^2 N(Z)] \text{ watts/cm}^3,$$

where the sum is over all ionization states Z.

Bremsstrahlung optical depth[40]

(31) $$\tau = 5.0 \times 10^{-38} N_e N_i Z^2 \bar{g} l T^{-7/2},$$

where $\bar{g} \approx 1.2$ is an average Gaunt factor and l is the physical path length.

Inverse bremsstrahlung absorption coefficient[41] for radiation of angular frequency ω:

$$K = 3.1 \times 10^{-7} Z n_e^2 \ln \Lambda / \omega^2 T^{3/2} (1 - \omega_p^2/\omega^2)^{1/2} \text{ cm}^{-1},$$

where $\Lambda = v_{Te}/V$, with V equal to the maximum of ω and ω_p, multiplied by the maximum of Ze^2/kT and $\hbar/(mkT)^{1/2}$.

Recombination (free-bound) radiation

(32) $$P_r = 1.69 \times 10^{-32} N_e T_e^{1/2} \Sigma \left[Z^2 N(Z) \left(\frac{E_\infty^{Z-1}}{T_e} \right) \right] \text{ watts/cm}^3.$$

Cyclotron radiation[25] in magnetic field $\mathbf{B}$

(33) $$P_c = 6.21 \times 10^{-28} B^2 N_e T_e \text{ watt/cm}^3$$

For $N_e k T_e = N_i k T_i = B^2/16\pi$ ($\beta = 1$, isothermal plasma),[25]

(34) $$P_c = 5.00 \times 10^{-38} N_e^2 T_e^2 \text{ watt/cm}^3.$$

Cyclotron radiation energy loss e-folding time for a single electron[40]

(35) $$t_c \approx \frac{9.0 \times 10^8 B^{-2}}{2.5 + \gamma} \text{ sec},$$

where γ is the total (kinetic plus rest) energy divided by the rest energy mc^2.

Number of cyclotron harmonics[40] trapped in a medium of finite depth l

(36) $$m^* = (57 \beta B l)^{1/6},$$

where $\beta = NkT/8\pi B^2$.

Line radiation is given by summing Eq. (9) over all species in the plasma.

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Most of the formules and data in this coiection are well-known and for all practical purposes are in the "public domain." The books and articles cited below are intended primarily not for the purpose of giving credit to the original workers, but (i) to guide the reader to sources contε'ning related material and (ii) to indicate where derivations, explanations, examples, etc., omitted from this compilation can be found. Additional material can also be found in D.L. Book, NRL Memorandum Report No. 3332 (1977).

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